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X-FAST (E**X**TERNALLY **F**ED **A**ERO**S**PACE **T**RANSPORTATION):

GENERAL FORMULATION AND ANALYSIS OF A TAKE-OFF AUXILIARY DEVICE

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FOREWORD

The aim of the activity is the research of the proof of concept and feasibility for the augmentation of rocket performance by means of an innovative auxiliary system, which is characterised by the presence of a static external reservoir of propellant (based on ground for this study), connected to the vehicle's body via a propellant transfer system. Such system's, namely X-FAST (e**X**ternally **F**ed **A**ero**S**pace **T**ransportation), peculiarity is in the fact that, when employed, the body of the vehicle is externally fed during the very first flight phase.

The target of the research is to:

- Propose a new method of utilisation that, from the point of view of science, technology and engineering can be another option to access to flight;
- Demonstrate that the concept does not require physics still to be developed and mainly uses already existing technologies;
- Demonstrate that for the part of the flight during which the X-FAST technology is employed, a better rocket law applies (with respect to a conventional comparative system);
- Increase the awareness of the technology readiness level for a technology demonstration.

The information disclosed in this thesis is part of a wider co-funded research project that AB Technologies has undertaken in the frame of a commitment with the European Space Agency (ESA).

The activity was held both at the European Space Research and Technology Centre (ESTEC) in Noordwijk, The Netherlands, and at the University of Naples "Federico II".

In the frame of the research it was possible to strongly benefit of the overall supervision of Prof. Annamaria Russo Sorge and of the fundamental support of Prof. Walter Grassi, University of Pisa, and of Prof. Luca Deseri, Universities of Molise and Carnegie Mellon.

In this work the X-FAST take-off auxiliary device is first formulated in a non-limitative manner, the main engineering issues are stated, some of the several solutions are presented and an analysis of the performance is given on an industrial launcher case. Further details were not disclosed as part of a wider co-funded ESA-AB Technologies research activity.

Please note: The aims of the research and the view are in strong accordance with the Visions and Missions of ESA and the European Commission. [(A) – *EC-ESA*, 2003], [(B) – *ESA*, 1998], [(C) – *ESA*, 2002], [(D,E) – *ESA*, 2003], [(F) – *EC*, 2003], [(G) – *EC*, 1998].

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In this occasion I would like to find words to thank and express my gratitude, in a non-limitative manner, to all those people who have supported me to make this achievement possible.

I would like to address my deepest sense of gratitude to Prof. Annamaria Russo Sorge for the feeling of tranquillity, of belonging and the overall un-replaceable supervision and technical support that she gave to me along all these years.

I finally find the chance to state and express with words the gratitude for the immense human, moral, scientific and technical support and dedication that I could generously receive from Prof. Walter Grassi and Daniele Testi from the University of Pisa and Prof. Luca Deseri from the Universities of Molise & Carnegie Mellon.

My thoughts are addressed to my colleagues and friends Marco and Davide and to the graduating Claudio from the AB Technologies team for their technical and human support. Their contribution was fundamental.

I would like to thank Prof. Antonio Moccia and the entire Doctoral Board for the general support.

My thanks are addressed to ESA, for the opportunity granted, and to all those people within ESA who effectively, with pure heart and mind, offered both sense of vicinity, technical support and, above all, human warmth and relief.

My friends, close and far, and some very special people I have had the fortune to meet during this path of life occupy a fundamental role and gave a non-replaceable contribution to this achievement and in this occasion I would like to thank them for everything.

I would like to address a kind thought to the young spirit and to the future engineers and managers of EUROAVIA-Napoli, which were always present along these years.

An affectionate thought is addressed to Paolo, which in the moments of difficulty has been one of my reference points.

I would like to thank the entire Avella and Rossano families, which always supported me, above all with thoughts and prayers.

My gratitude is addressed to my entire family. No words can express such feeling. My family is my real treasure.

I thank Salvatore for the privilege of having met him in this life, for all what he means to me and for all what he has done to make this work possible.

I dedicate this work and all my efforts to my mother, my father, Salvatore, the missing and never forgotten Enzo Ancarola and Roberto Avella.

Biagio Paolo Antonio

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NOMENCLATURE

a	Acceleration	[m/s^2]
A	Area	[m^2]
C_D	Drag Coefficient	[-]
f	Darcy-Weisbach-Moody Friction Factor	[-]
F	Force	[N]
g	Gravity Acceleration	[m/s^2]
h	Altitude	[m]
I_{sp}	Specific Impulse	[s]
L	Length	[m]
m	Mass	[kg]
$\dot{m}$	Mass Flow Rate	[kg/s]
M	Mach Number	[-]
P	Pressure	[Pa]
q	Dynamic Pressure	[Pa]
R	Radius	[m]
Re	Reynolds Number	[-]
s	Thickness	[m]
t	Time	[s]
T	Temperature	[K]
V	Velocity	[m/s]

μ	Dynamic Viscosity	kg/(m s)]
∇	Gradient Operator	[1/m]
θ	Angular Co-ordinate	[°]
ρ	Density	[kg/m^3]
σ	Stress	[Pa]
τ	Shear	[N/m^2]
ξ	Rectified Co-ordinate	[m]

A mia madre e mio padre

A Salvatore

Ai compianti ed indimenticati Enzo e Roberto

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1 INTRODUCTION

The low efficiency of today's conventional launchers and space transportation systems is caused by the high ratio between mass at launch and mass once the operational flight conditions have been reached, according to the type of mission for which the system has been considered.

The high value of the mass ratio is caused by the fact that the highest part of propellant, used to allow the vehicle to accelerate, is needed to carry along the path and accelerate the propellant itself together with the structure and the remaining elements of the vehicle.

Conventional rockets functioning is, hence, based on the main idea of carrying the entire mass of propellant needed along the flight and, for multistage rockets, jettisoning the lower stages as soon as the propellant has been consumed, in order to decrease the total mass along the path.

It is hereafter proposed a way to increase launcher performances by means of an innovative take-off auxiliary device, namely X-FAST (e**X**ternally **F**ed **A**ero**S**pace **T**ransportation). Such system allows decreasing the amount of overall mass at launch, keeping in mind that thrust shall be generated in order to accelerate the vehicle. In order to achieve this goal, **the thrust can be generated by the propulsion systems of the lower stages of the vehicle via a propellant/energy source kept external to the vehicle**.

At a certain point in time the limits of an existing technology and its own method of utilisation should be accepted and new ways to aim to the same targets, with higher performances, shall be assessed and combined to the already existing technologies to obtain benefits in the medium-long term.

Vehicles, such as the one proposed for the study rely on the idea of making lighter the overall system, by reducing the propellant/energy source mass. In common use already well tested terrestrial transportation systems, which rely on this idea, can be found. Examples of this type are wired trains, trams, wired buses, etc. All these transportation vehicles continuously find/receive, along the path, energy generated by a plant, located elsewhere, through the power cables. That is, the energy needed by the vehicle to propel itself is always found when it is "needed". Hence, for such systems, a good part of the propellant mass can be relocated in favour of a "heavier" payload.

The auxiliary system type and method of utilisation considered for this study falls in the category of unconventional aerospace transportation systems, based on advanced propulsion methods of utilisation but mainly relying on already existing technologies. Example of such types of systems, often called propellant-less systems, can be found in the literature (see rail-guns, solar sail systems, laser propulsion, etc.).

Rail-gun and solar sail systems have proved high potentials, but still research shall be performed and technology shall be developed to allow their common use in future space transportation. However many of the "propellant-less" space transportation systems could not allow missions with heavy payloads, at least if the short-term technology developments are considered.

The main contribution to the increase of launcher performance of such types of systems is caused by the fact that the propellant mass contribution, or a part of it, is removed from the rocket equation.

Conventional rocket systems are able to accelerate transportation vehicles carrying the whole amount of propellant needed during the entire mission. The basic concept of a conventional space transportation system is typically described by the Tsiolkovsky equation as follows [(1) – *W.J. Larson, J.R. Wertz*, 2000], [(2) – *A. Russo Sorge*, 1984]:

$$\Delta V_{Ideal} = c \ ln \ (m_{initial}/m_{final}) = I_{sp} \, g_0 \ ln \ (m_{initial}/m_{final}), \qquad \text{Eq. 1}$$

where ΔV_{Ideal} represents the ΔV achieved by the vehicle not considering drag effects and the presence of a gravity field. Moreover, c is the exhaust velocity, $m_{initial}$ and m_{final} are the initial and final masses of the rocket, I_{sp} is the specific impulse and g_0 the gravity acceleration. Eq. 1 directly derives from the main assumption of carrying the whole propellant mass on board the vehicle. Hence the Newton's law is simply written considering the total vehicle mass as a varying function of the time [$m = m(t)$]. It has to be noted that:

$$m_{initial} = m_{propellant} + m_{structure} + m_{payload}, \qquad \text{Eq. 2}$$

$$m_{final} = m_{structure} + m_{payload}. \qquad \text{Eq. 3}$$

So, considering I_{sp} fixed, the only way to increase the ΔV is by increasing greatly the $m_{propellant}$. Indeed, for typical lower stages of liquid propellant rockets, the term $m_{propellant}$ is of the order of 70% of $m_{initial}$. Hence, **if a more efficient propulsion method of utilisation can be provided**, even a small reduction to the amount of propellant gives a strong advantage in terms of payload mass increase.

For the proposed system, instead, this inconvenience is, at least partially, disregarded by removal of the propellant mass from the rocket equations. The envisaged system is capable to obtain an expression for Eq. 1, which is linear, in first approximation, and not logarithmic. Hence:

$$\Delta V_{Ideal} = c\ m_{propellant}/m_{final} = I_{sp}\ g_0\ m_{propellant}/m_{final}. \qquad \text{Eq. 4}$$

This equation is obtained under the restrictive hypothesis according to which the the instantaneously incoming mass, which is in liquid phase, numerically equals the mass instantaneously ejected from the nozzle/s of the first stage, in gaseous phase ($\dot{m}_{in} = \dot{m}_{out}$).

The clear advantage of this new model is shown in figure 1, where typical plots of Eq. 1 and Eq. 4 are compared. In particular, for a fixed ΔV, the required mass ratio of the conventional rocket is always and substantially higher than the one of the proposed system [(3) – *B. Ancarola*, *S. Bonifacio*, 2003].

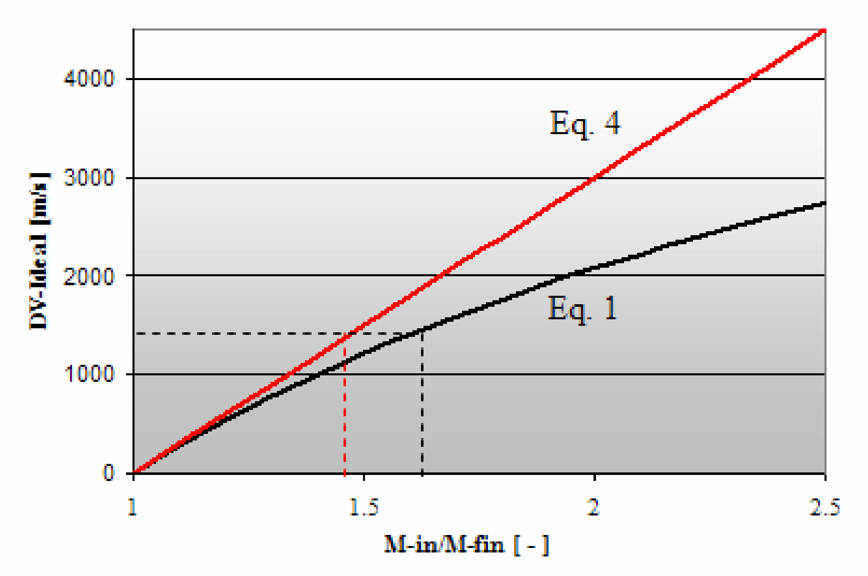

Figure 1 – Qualitative comparison between Eq. 1 and Eq.4 (for I_{sp}= O(300) [s])

From equation 4 it shall be noticed that the mass term at the denominator is a constant term during the X-FAST flight phase. On the other hand the $m_{initial}$ represents the hypothetical mass of a comparative conventional system employing the same amount of propellant. The initial mass can be evaluated adding the mass of effectively employed propellant to the initial mass. In order to compare the two methods, once defined $r = m_{final}/m_{initial}$, equation 4 plotted can be stated again as

$$\Delta V_{Ideal} = c\,(r - 1) \qquad \text{Eq. 4a}$$

The best feature of this figure is in the understanding of the fact that the proposed method of utilisation enables to allow a "better rocket-law", from logarithmic to linear.

2 X-FAST: GENERAL SYSTEM OVERVIEW

As stated in the introduction the way to achieve and mathematically obtain the removal of the propellant mass in the determination of the rocket equation is equivalent to feed externally the body of the vehicle for the part of the flight during which the concept applies.

Operationally one of the possible methods to set the transportation system is to configure it in such a way that it includes:

- A lower stage;
- Zero or more middle stages;
- An upper stage with payload;
- At least one ground based propellant reservoir and pumping system, necessary to feed the propulsion systems of the vehicle's body and kept apart from it;
- At least one propellant transfer system to connect the reservoir to the vehicle's body. The transfer system considered being an umbilical tube through which a fluid propellant flows under the pushing action of the ground based pumping system;
- A ground infrastructure.

For this system the mass of propellant then necessary to feed the engines of the lower stage is kept separated from the vehicle's body: the **<u>propellant follows the vehicle</u>** and its mass, in this case, is kept constant along the flight.

As a consequence the thrust generated by the engines of the lower stage can be fully used to accelerate the vehicle and not the propellant. The propellant transfer towards the vehicle's body occurs through an umbilical tube that connects the ground propellant reservoir to the lower stage of the vehicle. The propellant flow is allowed by the pumping systems based on the ground.

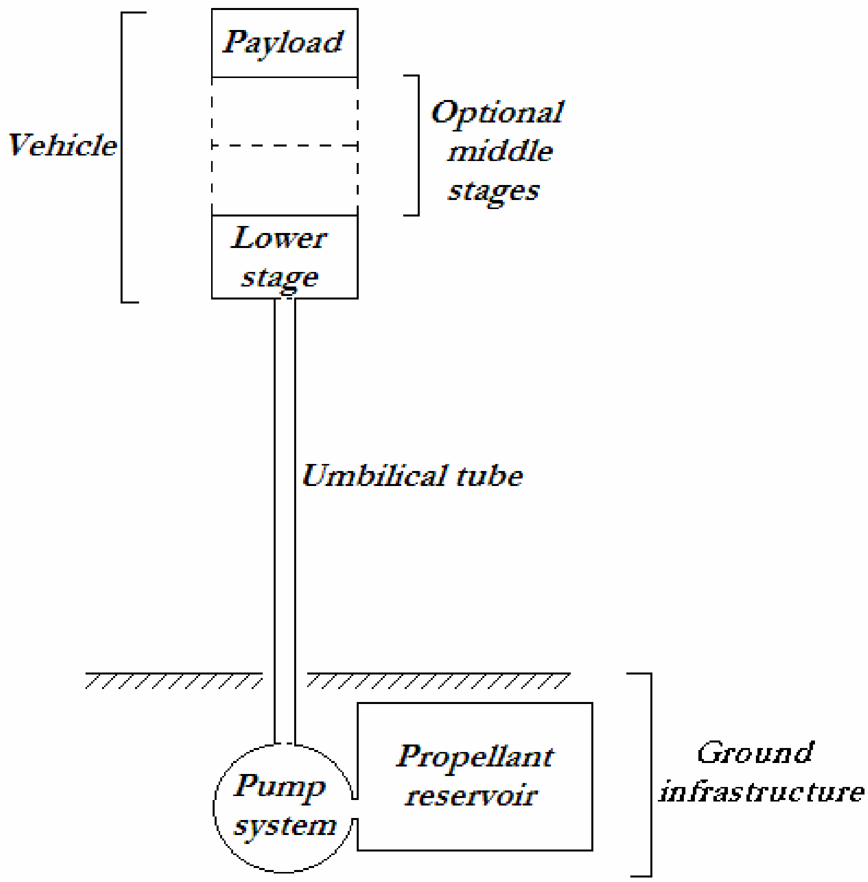

Figure 2 – General system scheme

The main characteristic of such concept, applied to a launch vehicle, lies in the **interface** between the propellant/energy reservoir and the vehicle's body. In literature different approaches have been considered to keep the **vehicle's body as dynamic** and the **energy reservoir as static**.

For this study, the assumption is made that the connection point between the pipe and the launcher is located at the base of the vehicle. In this case the pipe imposes a force, which lies on the same axis of the vehicle.

Only one pipe has been considered in linking reservoir and vehicle. However, if needed, other pipes could be added to the system and other pumps can be set on the ground base. This could increase the number of ground tanks to be set.

Conventional launchers feeding systems require the whole amount of propellant to be stored inside the vehicle. For bi-propellant rocket systems, since the combustion requires fuel and oxidiser, two tanks have to be disposed in each stage.

For what concerns the X-FAST concept, a choice can be done: the external feeding system should/could provide one of the two chemical components, whereas the other one should be already stored onboard the vehicle.

However, an empty (or partially empty) pressurised tank can be employed in the launcher to receive the incoming propellant.

Disregarding the external system and the interface, the rest of the vehicle's body and the internal feeding systems behave in a conventional manner.

Depending on the flight mission, the pipe can assume a certain attitude with respect to the vehicle's body and the ground base. However it should be noted that the utilisation of the X-FAST concept is limited to the very first part of the flight, when the vehicle is still performing, in a good approximation, a vertical ascent. One can imagine the duration of such phase in the range of the first 50 seconds after the lift off. Moreover this duration can become shorter or slightly larger depending on the intrinsic characteristics of the vehicle sizing and thrust over weight ratio.

The simplest pipe's flight configuration is the one achieved during the vertical ascent: when the pipe's axis overlaps the vehicle axis, the system configuration is axis-symmetrical. In this case no torque is explicated by the pipe on the vehicle, and the force caused by the pipe's weight and inertia lies on the axis.

If needed, appropriate attitude control systems are installed on board the vehicle in order to achieve a safe flight. According to the vehicle design, when the operational conditions are met, the lower stage and/or the tube are/is jettisoned.

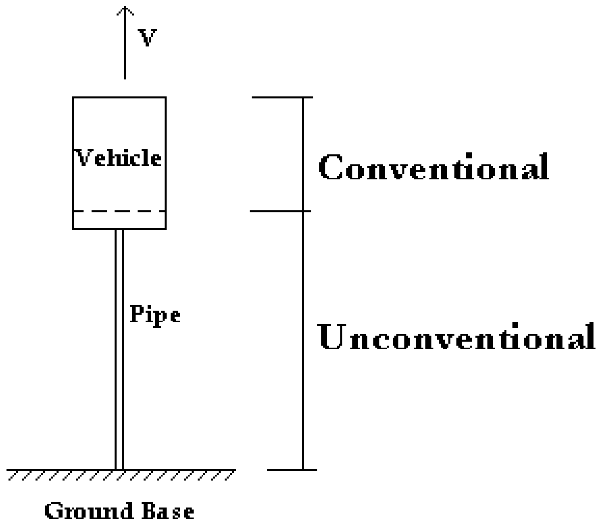

Figure 3 – Qualitative hose motion w.r.t the ground base and vehicle

2.1 BENEFITS AND CLASSES OF LAUNCHERS

In a non-limitative manner no assumptions on the number of employable stages has to be made. This because, depending on the size, class of the launcher and number of stages, the advantages have repercussions on the higher stages.

Such gains can be intended in different manners, depending on the types of mission objectives: higher payload, higher speed at a specific flight phase and condition, lower lift-off mass, longer range, higher maximum or apogee altitude, logistics savings, unburdening of the issues related to the generation of power in flight because of the rationalised usage of the ground infrastructure, and other relevant ones.

For this study the hypothesis is made that the ground based pumping systems push the propellant towards the vehicle's body in such manner that the instantaneously incoming mass, which is in liquid phase, numerically equals the mass instantaneously ejected from the nozzle/s of the first stage, in gaseous phase ($\dot{m}_{in} = \dot{m}_{out}$). From this hypothesis already important advantages spurt.

However, it can be noticed that such hypothesis is a restrictive one; indeed one can think of externally feeding the vehicle's body in such manner that the mass of propellant instantaneously incoming is higher than the one outgoing the nozzle/s of the first stage ($\dot{m}_{in} > \dot{m}_{out}$). Such assumption is equivalent to state that the body of the vehicle is a dynamically increasing mass system. Moreover, a choice of this type is equivalent to state that, operationally, a fraction of the tanks is kept unloaded at lift-off, while getting filled during the ascent, allowing a further unburdening of the system. Under the last hypothesis further high advantages can be achieved in terms of lightening and re-rationalisation of the X-FAST technology application. However such hypothesis is not considered purpose of this study.

For example, taken a comparative conventional system, fixed mission type and strategy, first stage burn-out altitude and release altitude of the hose, the whole amount of surplus in potential stored propellant, obtainable via the employment of the X-FAST take-off auxiliary device, can be directly redistributed among the vehicle stages and payload, producing the wanted advantages.

Such observation is visualised in the following figure.

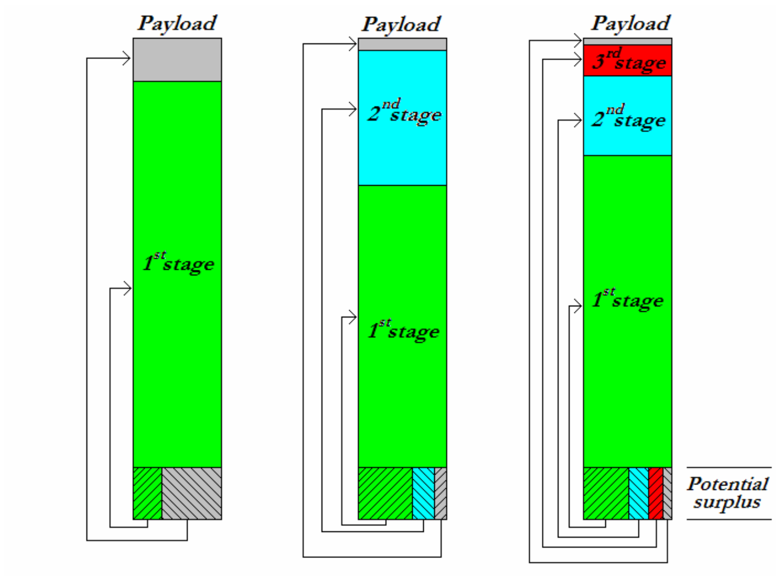

Figure 4 – Potential surplus redistribution scheme for single, double and triple stages rockets, for three different missions/applications types

The reader can have a preliminary comprehension of the type of gains to be expected via the application of the X-FAST technology to a conventional launcher class by noticing that its employment allows the reduction in class for size, and the increase of class for launch capabilities, hence allowing such gains in two directions.

The previous statements can be schematically explained through the following figure.

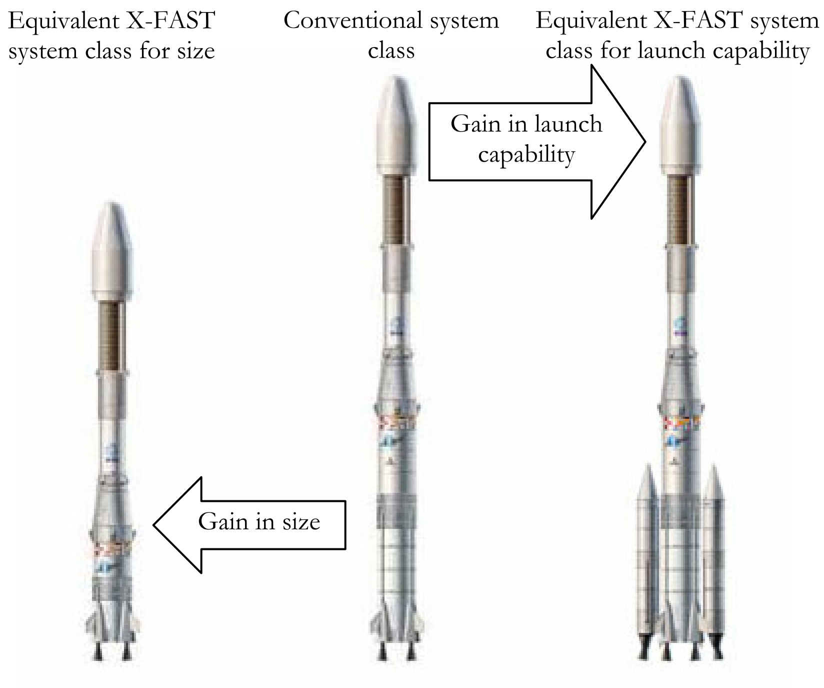

Figure 5 – Explanatory scheme related to the reduction in size and the increase in launch capability

2.2 State of the Art of the Main Involved Technologies

2.2.1 Vehicle

According to the configuration and the design choices, the conceptual changes to be made on a conventional vehicle type, in order to adapt it to an externally fed system, mainly concern the interface with the propellant transfer system.

Depending on the flight strategies, a generic conventional vehicle has to conceptually be modified and redesigned only for the first stage. In a non-limitative manner, the first stage can be provided with a tank reduced in size, in case the incoming propellant instantaneously occupies the volume emptied by the one outgoing, otherwise with a dedicated additional tank and related plumbing, arranged for the incoming propellant. Moreover an unfastening system has to be mounted in order to jettison the hose when desired flight conditions are met.

Furthermore, in order to obtain the full advantage by the utilisation of the X-FAST technology, one can think of a resizing also of the upper stages. Indeed, if for the same mission it is possible to employ a vehicle with a lower launch mass, one can think that such reduction can positively affect the resizing of tanks, structures and engines. However such last specific changes can be considered as resizing and not as technological and conceptual modifications.

2.2.2 Pumping Systems

The propellant transfer problem introduced by the concept can be schematised as the one of a fluid mass, present on ground, to be transferred towards a vehicle in vertical motion in order to allow it to perform its mission.

One of the requirements of such mission shall be that, when the release of the pipe occurs, the entire mass of propellant, present on ground at lift-off, is transferred to the vehicle's body. Moreover, the mission is such that when the release occurs the hose is fully filled of a low-density inert fluid.

Such choice is dictated by the engineering will to [(4) – *AB Technologies*, 2004], [(5) – *B. Ancarola*, *W. Grassi*, *D. Testi*, 2004]:

- Reduce the amount of power needed by the pump to push the propellant towards the vehicle;

- Reduce the dynamic height of a useless column of propellant and any possible fall of propellant at hose detachment;

- Create a physical disconnection between the base front of the propellant column present in the hose and the ground infrastructure.

The system responsible for the satisfaction of such mission needs is the pumping system, which is located on the ground and disposed at the base edge of the hose connecting the ground infrastructure to the vehicle's body.

The pumping system that satisfies the requirements presented is mainly composed of two conceptual blocks:

(A) Propellant pumping block;

(B) Low density fluid pumping block.

The propellant pumping block (A) functions from lift off up to the moment t^* when the amount of propellant to be transferred to the vehicle's body has been entirely expelled out of the propellant reservoir.

The block (B) starts functioning immediately afterwards. Its main task is to warrant a safe transfer of the propellant, still present in the hose, by means of the generation of a flow of low-density fluid along the line. Such flow is able to impose a time varying pressure law, which is the one defined by the intrinsic kinematics of the transfer.

The following plots give the reader an idea of the engineering advantages obtained by the introduction of a low density fluid in the flow through the hose [(6) – *N.P. Cheremisinoff*, 1990], [(7) – *R.V. Giles*, 1962], [(4) – *AB Technologies*, 2004].

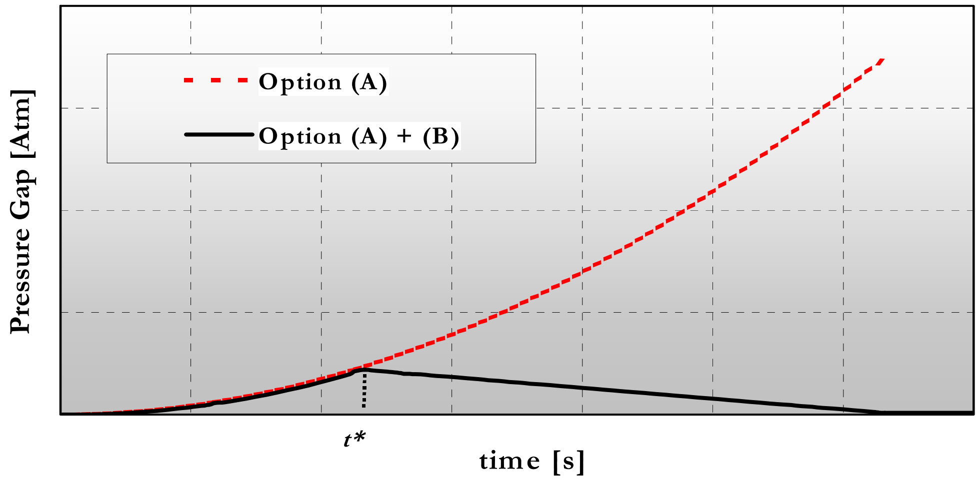

Figure 6 – Qualitative pressure gap comparison with/without option (B) for a medium/large launcher class

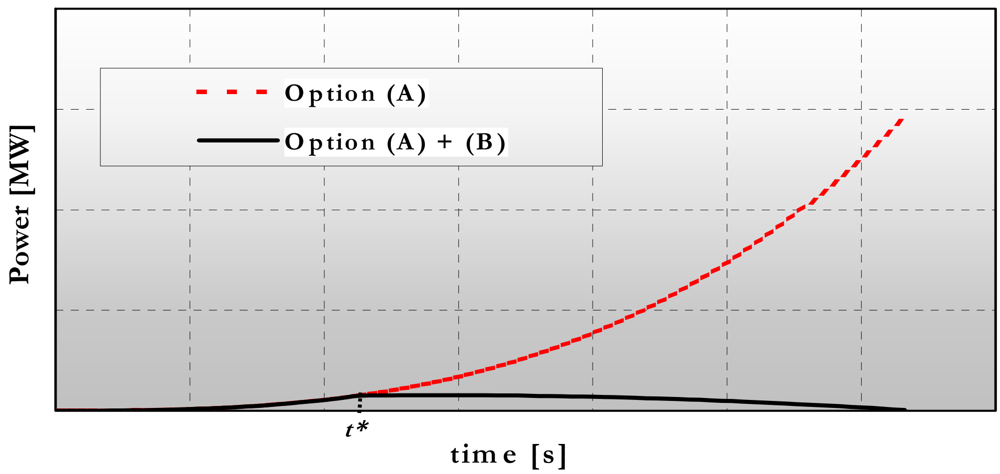

Figure 7 – Qualitative power comparison with/without option (B) for a medium/large launcher class

In particular, from the previous plot it can be noticed that the peak of pressure, measured at the base edge of the pipe, occurs at *t**. In case the low-density fluid would not be introduced, such pressure peak would occur at the moment of release of the hose and its magnitude would be 1 order higher. However, if the altitude of release is higher, the magnitude increases of 2 orders.

The order of magnitude of the peak of power depends on various factors. The most strongly affecting ones are the vehicle size and the altitude at which the hose is released.

To get an idea of the magnitude of the peak of power, it can be shown that for an Ariane 40 launcher type and an altitude of release in the range of $10^{0\div1}$[Km] such peak remains in the range $10^{0\div2}$[MW]. Moreover the average value of the power in time is typically lower than a half of the peak.

Systems that require such types of power are well tested and used in common every day life. Power plants, created and dedicated to high scale testing wind tunnels, consume amounts of power of the same and even higher order of magnitude with respect to the system proposed. Examples of such types are the *Plasmatron* [(8) – *V.K.I.*] high enthalpy facility, requiring 10^0 [MW] and the *Scirocco Hypersonic Plasma Wind Tunnel* (PWT) [(9) – C.I.R.A.], requiring 10^2 [MW], employed for high scale testing of re-entry bodies with time duration in the order of $10^{3\div4}$ [s].

3 X-FAST: ENGINEERING ARGUMENTATION

3.1 VEHICLE'S BODY

The employment of an X-FAST take-off auxiliary device does not require the complete conceptual re-design of a launch system. Indeed, for what concerns the utilisation and the operation of the main body of the considered vehicle, after hose release the selected rocket becomes a fully conventional system.

Therefore, in a non-limitative manner, when adopting the choice of employing an X-FAST device, the vehicle can be composed of a pre-stage for the X-FAST flight phase adapted/attached to a main body stage for the subsequent conventional powered flight phase.

The main design drivers for the definition of the configuration of the vehicle's body shall be directly related to the need of keeping the shape and the distribution of the single elements within the structure as close as possible to widely tested and employed solutions. For example, the slender single body configuration can be considered for its simplicity.

One of the critical issues imposing strong choices for the definition of the configuration is dictated by the need to limit any eventual interaction between the propellant transfer system and the plumes generated by the engines of the rocket.

As a consequence of this need, the top edge of the hose is co-axially connected to the lower part of the vehicle's body.

Under such assumption a typical choice can be made to employ two or more engines. The engines shall be disposed in such manner that their axes are symmetrical and co-planar with respect to the symmetry axis of the vehicle's body.

Such type of overall configuration solution is typically employed for wire guided rockets and allows even for reduction in eventual dynamic instability of the vehicle.

The definition of the overall vehicle's body design shall take into account several engineering disciplines such configuration and elements distribution, missiles aerodynamics, propulsion, stability and control, structures, guidance, navigation and communication. However, such argumentation involves the use of knowledge already consolidated in the past decades. This is due to the fact that the vehicle's body does not conceptually require drastic modifications, but mainly engineering adaptations in order to comply with type of motion achieved during the very first part and low subsonic phase of the flight.

Further literature on the argument has been developed in the frame of the wider X-FAST research project and its introduction is out of scope of the present documentation [(4) – *AB Technologies*, 2005].

3.2 PROPELLANT TRANSFER SYSTEM: MAIN FEATURES AND ENGINEERING REMARKS

The top edge of the hose is considered connected to the rear side of the vehicle's body at its base. During the externally fed phase of the flight, which is supposed as a vertical ascent according to the literature of widely industrialised rockets and to the engineering will, the umbilical tube is maintained, as long as the vehicle departs from the reservoir's location.

The vehicle moves in such way that the hose does not (remarkably) interact with the mass flow outgoing the nozzle/s of the engine/s properly disposed on board the lower stage. As typically done for other types of applications, this can be satisfactorily achieved for the X-FAST application by means of properly disposed thrust vector control (TVC), eventually employed if the overall missile configuration requires it [(4) – *AB Technologies*, 2005].

The kinematics of the flow through the part of the hose, instantaneously ascending, can be subdivided in two phases as follows:

1 Starting from the lift-off ($t=0$), the pipe is filled while extending and the propellant flows through it, being the only fluid present inside.

2 When the whole amount of propellant to be transferred is expelled from the ground based reservoir ($t=t^*$), a low density inert fluid is employed and introduced in the line in order to push the remaining propellant, still present in the pipe, towards the vehicle's tank ($t^*<t<t_{release}$).

Considering the entire externally fed mission, the reader can notice that at t^* the column of propellant reaches its maximum length. The amount of propellant instantaneously stored in the pipe, its weight and its acceleration, with respect to an observer fixed on the ground, define the instantaneous value of the pressure gap. Hence at t^* the peak of pressure shall be expected.

$t_{release}$ represents the instant in which the whole amount of propellant ends being transferred to the vehicle, and the releasing of the pipe is performed.

Concerning the shape of the hose, the assumption of having a constantly fixed cross-section is not a must. This because the hose can be thicker where the total pressure of the fluid is nearby its maximum, thinner where the pressure decreases [(4) – *AB Technologies*, 2005], [(10) – *B. Ancarola*, *L. Deseri*, Aug. 2003].

When a hose with a constant thickness has to be designed, the value of such thickness should be the maximum one needed for insuring the non-failure of the pipe's structure. Already a linearly decreasing thickness versus rectified co-ordinate would allow an enormous reduction of the pipe mass, which would mean in an even more sensible reduction in the average-mass-of-the-pipe in time, representing a measure of the possible reduction of the traction force.

For what concerns the size of the internal radius of the hose, it should be decided depending on the mission requirements.

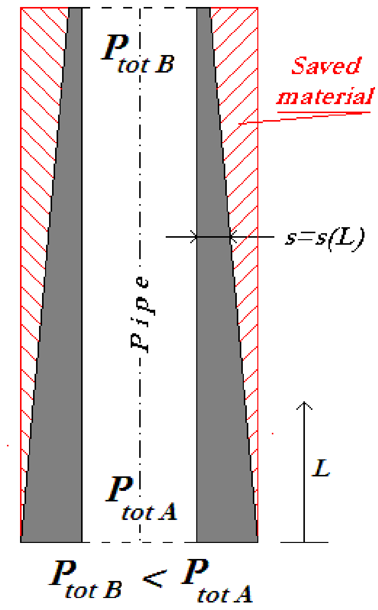

Figure 8 – Qualitative scheme of a pipe with a variable thickness

In order to determine the optimum size and shape, several design iterations and steps have to be done.

The next paragraphs briefly explain the physics of the design problems involved and the engineering considerations and assumptions to be made.

3.2.1 MECHANICAL LOADS

The types of loads mainly characterising the design and sizing of the propellant transfer system are [(11) – *B. Ancarola*, 2003]:

- Axial loads due to the weight and the inertia of the hose;
- Circumferencial loads due to the local internal pressure distributed along the hose.

3.2.1.1 AXIAL LOADS

The vertical ascent of the vehicle's body imposes, as a consequence of the mechanical consistency, the motion of the top edge of the hose. For mechanical continuity the lower sections of the hose have to follow the vehicle's body. Such motion imposes the establishment of a traction force along the axis of the hose, which force generates a distributed axial tension.

The presence of the traction force, acting on the vehicle's body, if not contained in its magnitude, might seem not to allow any gain. However taking into account the average value of the mass suspended in time from lift-off up to release, one can get a better understanding of the influence of the hose on the motion of the vehicle's body centre of mass.

In order to do so, if a simple approximation is made of a constantly accelerating body in the vertical direction, hence linearly increasing in velocity, the altitude versus time law is parabolic, so quadratic. This is legitimate if the time variation, Δt, is in a short range, as confirmed by Taylor's theory [(12) – *V. Ferone*, 1996], [(13) – *L.R Burden*, *J.D. Faires*, 2001]. It is even more legitimate if one takes a look at the diagrams z=z(t), so altitude versus time, for $\Delta t \in [0, 100]$[s], for various launchers such as Ariane 5, Ariane 4, Atlas 2, etc [(14) – *S.J. Isakowitz*, 2000], [(15) – *Arianespace*, 1999], [(16) – *CDF*], [(17) – *B. Ancarola*, 2002].

It is verifiable that the law is, by a certain level of approximation and good accuracy, quadratic. However a power law in time could be considered.

To have an engineering feeling of the influence of the presence of the external body on the motion of the centre of mass of the vehicle, one can think about introducing the average mass of the pipe, which is a measure of the average amount of hanging mass.

Under the previous assumption it can be analytically shown that the average value of the mass of a pipe, with constant cross section, pulled by the rocket along the ascent is one third of its deployed mass.

The following figure shows offers an understanding of the previous statement.

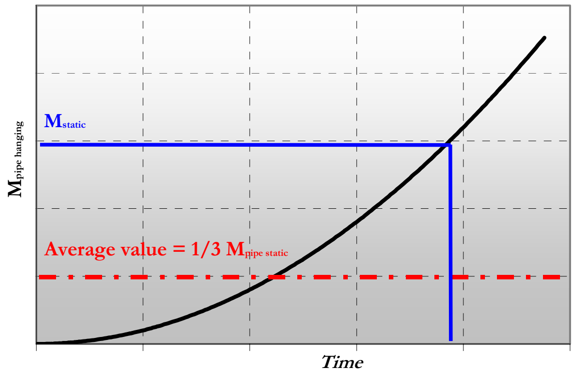

Figure 9 – Average mass along the deployment

Considering the specific orders of magnitudes involved for the evaluation of the axial loads, under certain simplifying but still extensive assumptions (no external skin friction, constant gravity field etc.), the axial stress in each pipe's cross section can be evaluated as follows [(18) – *L.D. Landau, E.M. Lifshitz*, 1970], [(10) – *B. Ancarola*, *L. Deseri*, 2003], [(11) – *B. Ancarola*, 2003]:

$$\sigma_\xi(\xi) = \rho g \left(1 + \frac{\ddot{z}_{cm}(t)}{g}\right)\xi \qquad \text{Eq. 5}$$

Where ξ is the rectified co-ordinate, ρ is the density of the propellant and $\ddot{z}_{cm}$ is the acceleration of the centre of mass of the vehicle.

Considering characteristic thrust to weight ratios for rockets of interest, and assuming the material used for the umbilical tube having a density of 10^3 [kg/m^3], a rough estimation of the previous equation says that $\sigma_\xi(\xi)<20000\cdot\xi$ [Pa]. Hence the axial stress generated at each cross section of the umbilical tube, constantly accelerating along the vertical direction, with a self-weighting term already considered in the motion, has a linearly increasing law as a function of the height z.

Hence, for such a system, even if the considered reference length is of the order $10^{2\div4}$ [m], the maximum tension encountered remains in the order of $10^{0\div3}$ [MPa].

Moreover taking into account even the sustaining lifting effect due to the viscous interaction, variable section theory and other engineering assumptions, the slope of the previous equation can decrease in value leading to a reduction of the magnitude of the maximum tension.

3.2.1.2 CIRCUMFERENCIAL STRESSES

As a consequence of the vertical motion of the umbilical tube and of the continuity for fluids, the propellant that instantaneously fills the pipe creates a column. In order to let such fluid column continuously follow the vehicle's body a distributed pressure is established along the axis of the pipe.

The maximum value expected at the base front of the propellant column and occurring at t^*, represents the dimensioning main fluid dynamic parameter for the design of the umbilical tube: this because the establishment of a generic pressure in the hose generates circumferencial stresses in the wall.

Indeed, circumferencial tensions are generally introduced in pipeline systems, and have to be strongly taken into account, when the total pressure of the internal flow becomes punctually so high, with respect to the considered problem, not to be negligible anymore [(10) – *B. Ancarola*, *L. Deseri*, 2003].

In order to obtain a pointwise evaluation of the pressure within the flow field and as a function of time, a detailed formulation of the fluid dynamic problem should be considered via the solution of the Navier-Stokes equations [(19) – *L. De Luca,* 1998], [(20) – *R.A. Granger*, 1985], under proper assumptions related to the motion of the walls.

However an accurate and general treatment can be performed invoking the solution of the problem for average values with respect to the generic station, taken along the umbilical hose.

In order to define the proper pipe's wall sizing, a material selection has to be done since the dimensioning equation, which rules the phenomenon, is strongly depending on the material properties.

Standard available materials, holding mechanical and thermal properties, whose information are obtainable consulting typical databases and engineering handbooks, already show their possible applicability with satisfactory employment [(21) – *TU-Delft,* 2002], [(22) – *ESA,* 1994].

Standard arguments in mechanics [(23) – *J.F. Harvey,* 1985], [(24) – *Timoshenko, S.P., Goodier, J.N.*, 1970], [(10) – *B. Ancarola*, *L. Deseri*, 2003] provide an expression for the evaluation of the circumferencial stress occurring in a thin pipe, internally loaded by a mass flow; this is done by taking into account the mean radius of the tube, the thickness *s* and the pressure as follows:

$$\sigma_{rr}(\xi)\Big|_{\max} = \frac{P_{\max} \cdot R_{Int\,Mean}}{s} \qquad \text{Eq. 6}$$

Where σ_{rr} are the longitudinal stresses inside the wall, P_{max} is the maximum pressure encountered, $R_{Int\ Mean}$ is the mean radius of the hose cross section and *s* is the wall thickness as shown in the previous equation. Hence the thickness can be determined inverting the previous equation for *s* and imposing the material type, by means of its maximum circumferencial allowable tension.

Thus if the maximum allowable circumferencial tension is of the order $10^{1\div3}$ [MPa], supposing in this specific case a $R = 0.2$ [m] and a peak of pressure in the order of $10^{0\div1}$ [MPa], the thickness remains of the order $10^{(-4)\div(-3)}$ [m], so of the order of fractions of millimetres.

One can show that the existing materials allow the realisation of such a tube, which should withstand a maximum circumferencial tension such as the one induced in the material by the presence of a pressurised rapid flow of mass.

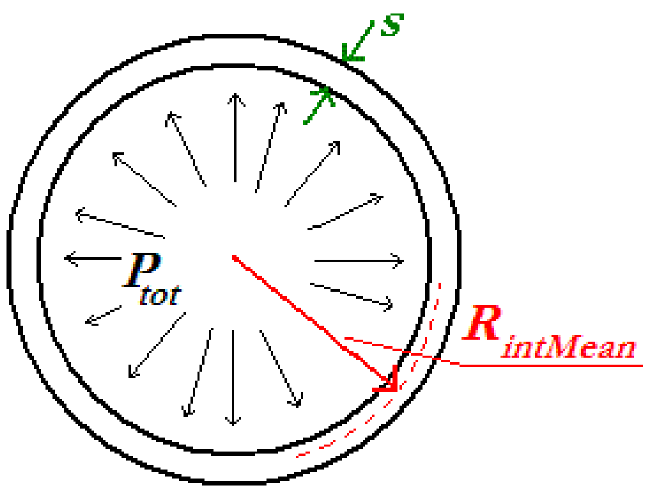

Figure 10 – Pipe section and pressure acting

3.2.1.3 Inner Skin Friction

Due to the intrinsic viscosity of the internal flow occurring in the hose, a shear can be expected at the inner side of the wall. Such phenomenon is typically defined as skin friction [(25) – *F.M. White*, 1974]. The integral consequence of a shear extended to the entire evolving inner wall of the hose can be directly translated into a sustaining lifting effect. Such skin friction gives an advantageous effect by lifting up the pipe since it acts in the same direction and verse of the launcher thrust.

The magnitude of such effect varies in a manner that is directly linked to the square of the relative velocity of the flow through the pipe [(26) – *R.D. Blevins*, 1984], as seen by an observer fixed on a pipe's cross section. One can affect such magnitude by defining the proper size of the pipe's internal diameter.

3.2.2 Thermal Loads

3.2.2.1 Internal Interaction

The pressure measured at the base front of the evolving propellant column flowing through the hose is a function of the length of the inner wall instantaneously wetted, the gravity acceleration and the inertia of the fluid.

An analysis of the orders of magnitude involved shows that these typical pressure values could reach their maximum at $10^{0\div1}$[MPa] depending on the mission, for a considerably massive launcher. Due to these pressure levels that the low-density fluid has to undergo, once it has been introduced in the line, a variation of the temperature and density might even be expected. During the design of the hose such issue shall be taken into account. Further details can be found in the wider treatment performed in the frame of the X-FAST research project [(4) – *AB Technologies*, 2005].

3.2.2.2 EXTERNAL INTERACTION

Depending on the configuration and the relative disposition of the engines of the first stage of the rocket and the propellant transfer system, if necessary, the thermal interaction between the hose external side and the exhaust flow field generated downstream the nozzle/s could/should be considered. The solution of such flow field can provide information related to the thermofluid dynamic domain in which the pipe lies. Preliminary analyses show that the temperature and the other relevant thermofluid dynamic parameters strongly decay to the ambient conditions, as the considered region is the one just outside the supersonic, hence very confined plume.

To get an idea [(27) – *L.G. Napolitano,* 1969], [(28) – *A. Ferri*, 1949] already considering the potential flow, since the supersonic motion of the gas is ruled by hyperbolic partial differential equations, the region of the plume is even mathematically confined into a restricted conical domain. Such region is the one in which the structure of the hose does not encounter dangerous thermal stresses. The confinement of the plume depends on the choices made by the designer of the nozzle. Literature data and preliminary analytical estimations report temperature values just at the outlet of the nozzle along its axis to be about 50 % of the maximum temperature set in the throat. This means that the maximum values of the temperatures in the core of the plume remain limited under 1500 [K] [(29) – *F. Sabetta*, 1999].

If necessary, the hose can be properly shielded against radiative heat transfer in the region of interest.

In the frame of the wider X-FAST research project, several analyses have been performed and the flow field generated outside the nozzles has been evaluated for typically industrialised rockets. According to such analyses the previously mentioned statements can be confirmed and satisfied. Further details can be found in the developed literature [(4) – *AB Technologies*, 2005].

3.2.3 HANDLING AND CHEMICAL PHENOMENA

For what concerns the X-FAST concept the external feeding operation requires the employment of one fluid propellant. Hence, in the most generic manner, the concept can be applied to rocket systems that make use of at least one liquid propellant.

The storage and the transfer of fluid propellants through a duct are operations that might induce cavitation phenomena. Such phenomena mainly occur for propellants characterised by high vapour pressures, within their ranges of application. Cavitation is a phenomenon to be avoided when the propellant flows directly in the combustion chamber, as it can induce combustion instabilities. However, for what concerns the X-FAST concept, in the most generic and non-limitative manner, such phenomenon is not binding because the system can be designed in such way that the propellant is not constrained to flow directly in the combustion chamber. Indeed, depending on the design, the propellant can be stored into a tank and kept at the proper conditions before usage.

Widely used liquid propellants employed for conventional rocket applications are Hydrazine, MMH, UDMH, Liquid Hydrogen, Kerosene as fuel, Nitrogen Tetroxide, Liquid Oxygen, Fluorine, Nitric Acid as oxidiser [(30) – *G.P. Sutton*, 1992], [(31) – *USAF*, 1977], [(32) – *F.A. Warren*, 1958]. However for this specific study no cryogenic technology is considered. Depending on the selected propellant to be externally transferred and the material of the hose, corrosive phenomena might occur due to the chemical interaction. During the design, if necessary, such propellant material coupling should be defined in a manner that would avoid corrosive interaction.

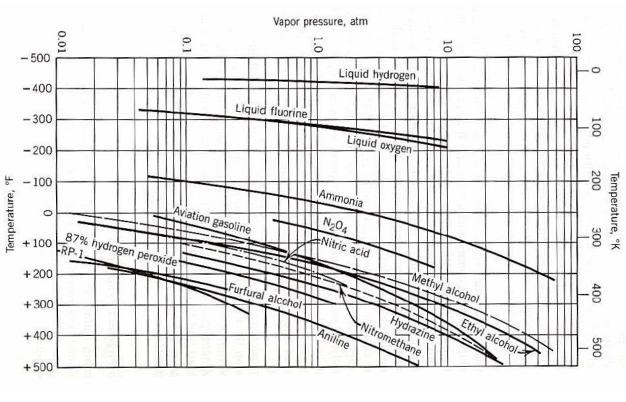

Figure 11 – Vapour pressures of liquid propellants as function of temperature

Further details can be found in the literature developed in the frame of the wider X-FAST research project [(4) – *AB Technologies*, 2005].

3.2.4 MATERIALS

During the design, the selection of the most appropriate materials has to take into account various factors such as mechanical characteristics, thermal ranges of applicability, flammability, degradation at fatigue and at storage, and other typical relevant features.

According to different sources of materials properties [(21) – *TU-Delft,* 2002], [(33) – *ESA*, Jan. 1994], [(22) – *ESA*, Feb. 1994] even simple pure materials, typically used for cabling and piping systems, have ranges of application of 1÷4 orders of magnitude higher than the ones foreseen to be employed for the systems under consideration.

In particular the combination of pure materials, leading to composite material structures, could then allow the propellant transfer system to withstand mechanical loads even in higher ranges, in case an extra over dimensioning might be needed.

For what concerns the design of the external side of the hose, just in the vicinity of the connection between the hose and the body of the vehicle, various materials and coatings can be considered.

According to researches conducted in the field [(34) – *NASA*, 2003], [(35) – *ESA*, Jan. 1994], [(22) – *ESA*, Feb. 1994], several interesting coating systems under production can be mentioned, having thermal behaviours satisfactory for the types of applications introduced by the concept.

Moreover, even woven materials (made of textile fibres), useful for flexible structures, can be employed because of their high service temperature and very high tensile strength.

For what concerns the chemical interaction issue several solutions can be offered; the inner wall of the hose can be coated with widely employed insulating paints/materials, which can withstand various eventual corrosive actions due to the contact with the propellant.

An appropriate engineering solution considers the utilisation of a multi-layered hose configuration [(4) – *AB Technologies*, 2005].

3.2.5 DEPLOYMENT

The deployment of the propellant transfer system, to be implemented for the X-FAST auxiliary device, has no past in literature since it has never been studied and implemented before, according to the sources available.

In order to avoid any sort of limitation, a specific deployment system is not described in this document.

However such system shall allow for vertical motion of the hose, being able not to offer extra-tensioning inputs along the line and adequate controllability of the vehicle's body. Widely used active control systems

Further details can be found in the literature developed in the frame of the wider X-FAST research project [(4) – *AB Technologies*, 2005].

3.3 STABILITY AND CONTROL

When an X-FAST auxiliary device is employed the vehicle shall move in such manner that the hose does not (remarkably) interact with the mass flow outgoing the nozzle/s of the engine/s properly disposed on board the lower stage. As typically done for other types of applications, this can be satisfactorily achieved for the X-FAST application by means of properly disposed thrust vector control (TVC), eventually employed if the overall missile configuration requires it [(4) – *AB Technologies*, 2005].

The vehicle's body dynamic stability and control was indeed studied considering the two oscillation modes: the short period (normal motion to the trajectory) and the long period-phugoid mode (tangent motion to the trajectory) in the pitching plane, under the intrinsic dynamics and several types of inputs.

This was done in order to assess the eventual gaps from the effectively desired motion and the achieved motion. Such wide analysis was performed showing that, under proper dimensioning and design assumptions, the employment of the X-

FAST auxiliary device onboard typical industrial rockets allows for an increase in the dynamic stability issues.

This is even due to the fact that, during the vertical ascent, the intrinsic attitude dynamics of the vehicle's body require a lower effort to be exerted by the TVC with respect to a conventional comparative vehicle.

Further details can be found in the literature developed in the frame of the wider X-FAST research project [(4) – *AB Technologies*, 2005].

4 X-FAST MATHEMATICAL MODEL

This chapter reports on the mathematical model for the description of the motion of a launch vehicle employing an X-FAST take-off auxiliary device.

The description of the motion for such system considers the several subdivisions in phases, underlining the importance to investigate on the flight phase during which the X-FAST technology is active. Fixed the thrust level, with respect to a conventional system, two mission strategies have been principally considered, as the extreme cases of an engineering method to approach the application of the concept. Intermediate strategies can be also employed when a trade-off analysis between these two approaches is considered. The description of such mission strategies is presented in paragraph 4.2.

The mathematical model applied to describe the motion of the centre of mass of the vehicle's body takes into account environmental, aerodynamic and propulsive features together with the ones introduced by the adoption of the X-FAST auxiliary device.

The main and fundamental engineering features and characteristics introduced by the X-FAST technology are explained in paragraph 4.9, where the engineering assumptions are imposed to the mathematical model and the natural engineering parameters are given.

At system level such parameters are mainly identified in those related to the tension and traction forces, (in particular the ones determined at the top edge of the propellant transfer system); the cross section diameter/radius and thickness dependency with respect to the rectified co-ordinate; the shear stress acting on the internal wall of the propellant transfer system due to the viscous interaction between the inner propellant flow and the hose; the pressure gap between the base and the top fronts of the propellant flowing through the hose, due to the difference in altitude and to viscous intrinsic phenomena; the hydraulic power to be supplied by the ground based systems, in order to allow a fluid propellant to chase and reach an ascending body; the sustaining lifting effect acting at the wall of the propellant transfer system, as consequence of an integral effect of the shear [(4) – *AB Technologies*, 2004], [(36) – *B. Ancarola, D. Starnone, M. Iannuccelli, D. Testi*, Dec. 2004].

The performance definition is delivered in terms of comparison, with respect to a conventional system, of the principal flight parameters through selected indexes and gains. Such gains can be intended in different manners depending on the types of mission objectives: higher payload, higher speed at a specific flight phase and condition, lower lift off mass, longer range, higher maximum or apogee altitude, logistic advantages, unburdening of the issues related to the generation of power in flight because of the rationalised usage of the ground infrastructure, and other relevant ones.

4.1 Description of the Motion

The motion of a launch vehicle is generally subdivided in phases. Such phases are introduced by discontinuities occurring during the flight events. Typically, these flight events are the ones related to the starting and the burning out of each specific stage or jettisoning of the fairing.

When employing the X-FAST take-off auxiliary device, another phase has to be considered for the part of the flight during which the vehicle's body is externally fed.

A launch system is composed of a number of stages (*n*), generally from 1 to 3 stages. To fix the ideas, still keeping generality, it can be chosen a vehicle with 3 serial stages to explain the phases of the motion. The following phase's subdivisions can be considered:

1. *Vertical ascent until X-FAST device release*. This phase occurs in the part of the flight during which the vehicle's body is externally fed. During this phase the flight is powered by the engines of the first stage. The ascent is vertical and the mass of the vehicle's body is kept dynamically constant, as the hypothesis of $\dot{m}_{in} = \dot{m}_{out}$ is employed. This hypothesis means that the amount of the propellant

mass, pumped by the external system and coming in the vehicle, is equal to the amount of propellant mass burnt and exhausted instantaneously.

2. *First stage phase.* After hose release, the flight continues in powered mode still thrust by the engines of the first stage, and the vehicle works in a conventional manner. This phase ends when the stage exhausts all its propellant (the largest part of its mass), and it is jettisoned to reduce the amount of the inactive mass that the next stage must propel. The vehicle's mass decreases because propellant is consumed during the flight and can be evaluated as follows:

$$m_{propellant}(t) = m_{propellant}(t_0) - n_{engines}\dot{m} \cdot (t - t_0) \qquad \text{Eq. 7}$$

where: t is the time; t_0 is its determination at *i-th* stage starting;

$m_{propellant}(t_0)$ is the initial propellant mass of the stage;

$n_{engines}$ is the number of engines of the stage;

$\dot{m}$ is the mass flow rate of each engine of the *i-th* stage.

3. *Second stage phase.* Also this phase is considered finished when the stage exhausts all its propellant and it is jettisoned.

4. *Jettison of the fairing.* The jettison of the fairing occurs in an approximate intermediate time between the first and the second stage functioning.

5. *Final-third stage phase.*

6. *Ballistic flight and final mission goal accomplishment.*

For this study the main interest is to investigate on the first and second phase, because an analysis on the entire rocket flight is not needed to give representative information on the innovation introduced by the proposed concept. The X-FAST technology is actually active only during the functioning of the first stage. The advantages can be extrapolated to the whole flight using typical mission analysis methodologies and properties of the final conditions achieved by the vehicle already at the first stage burn out.

4.2 MISSION STRATEGIES

Fixed the thrust level, with respect to a conventional system to which an X-FAST take-off auxiliary device adapted, two mission strategies have been principally considered to approach the concept.

The *first strategy* aims at obtaining a minimum lift-off mass, cutting unused structural mass and eliminating propellant mass, which is externally fed. This mission approach can be summarised, in terms of vehicle's body mass, as follows:

$$m^{X-FAST} = m_{conv}(h_{release}) - \delta \qquad \text{Eq. 8}$$

where: δ represents a tuning factor depending on the full usage of the capacity of the first stage.

Hence, the first strategy can be defined in such manner that the numerical value of the mass of the unconventional vehicle, from the lift-off up to release of the hose, remains equal to the mass that the conventional one holds at the pipe's release altitude.

The expected result is a decrease of the initial launch mass of the vehicle to which the X-FAST technology is applied and an increase of the achieved velocity at the tube's release altitude, with respect to the initial mass and velocity of the comparative conventional system considered.

The *second strategy* can be implemented in order to obtain a maximum potential propellant mass on board (with respect to a comparative conventional case), after the pipe's release. In terms of vehicle's body mass the previous statement can be defined as follows:

$$m^{X-FAST} = \tilde{m}_{conv}[h(t_{release})] - \delta \qquad \text{Eq. 9}$$

with:

$$\tilde{m}_{conv}[h(t_{release})] = \frac{t_{release}}{\int_0^{t_{release}} \frac{1}{m_{conv}(t)} dt} \qquad \text{Eq. 10}$$

Hence, the second strategy can be defined in such manner that the numerical value of the mass of the unconventional vehicle, from the lift off up to release of the hose, remains equal to the average, versus time, of the mass of the conventional system, evaluated between the initial time (zero) and the time corresponding to the pipe's release altitude.

The result is still a reduction of the initial mass (but lower than the one obtained with the first strategy), the same velocity at the release altitude (with respect to the velocity of the comparative conventional vehicle) and a potential surplus of propellant mass stored in the first stage to which the X-FAST concept is applied.

Such amount of potential surplus in stored propellant, obtainable at the release of the hose, can be directly re-distributed among the vehicle stages and payload to achieve the mission objectives, producing the wanted advantages.

Such intuition is shown in the following figure.

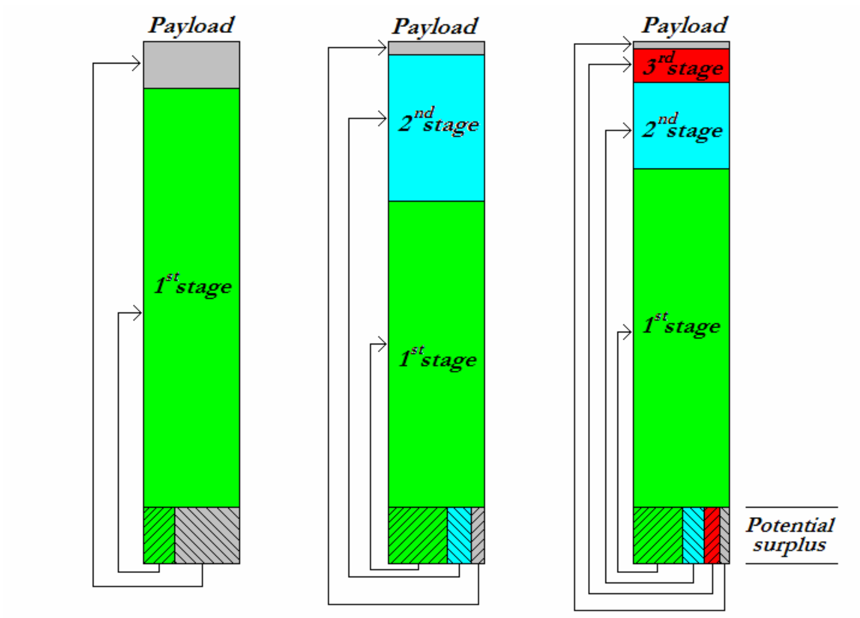

Figure 12 – Potential surplus redistribution scheme for single, double and triple stages rockets, for three different missions/applications types

Again, for this study the hypothesis is made that the ground based pumping systems push the propellant towards the vehicle's body in such manner that the instantaneously incoming mass, which is in liquid phase, numerically equals the mass instantaneously ejected from the nozzle/s of the first stage, in gaseous phase ($\dot{m}_{in} = \dot{m}_{out}$). From this hypothesis already important advantages spurt.

However, it can be noticed that, such hypothesis is a restrictive one; indeed one can think of externally feeding the vehicle's body in such manner that the mass of propellant instantaneously incoming is higher than the one outgoing the nozzle/s of the first stage ($\dot{m}_{in} > \dot{m}_{out}$). Such assumption is equivalent to state that the body of the vehicle is a dynamically increasing mass system. The implementation of such hypothesis requires further specific analysis and mathematical treatment and it is not considered for this study.

According to the arguments presented in this paragraph, the reader can get a comprehension of the fact that the advantages due to the utilisation of an X-FAST auxiliary device can be intended in different manners, depending on the types of mission objectives: higher payload, higher speed at a specific flight phase and condition, lower lift-off mass, longer range, higher maximum or apogee altitude, logistics savings, unburdening of the issues related to the generation of power in flight because of the rationalised usage of the ground infrastructure, and other relevant ones.

4.3 VEHICLE'S MODEL

A launch vehicle is a system finely tuned and a very complex device, made by several interconnected subsystems. It is composed of a number of separable sections (stages); and each stage is composed by propellant tankage, propulsion systems, and control systems structural elements [(2) – *A. Russo Sorge*, 1984], [(37) – *O.H. Lang*, *R.J. Stein*, 1963].

As each stage exhausts all its propellant (the largest part of its mass) it is jettisoned to reduce the amount of mass that the next stage must propel, also reducing the amount of energy required to lift the remaining vehicle mass [(30) – *G.P. Sutton*, 1992].

In the following figure a generic overview of a three stages launch system is represented.

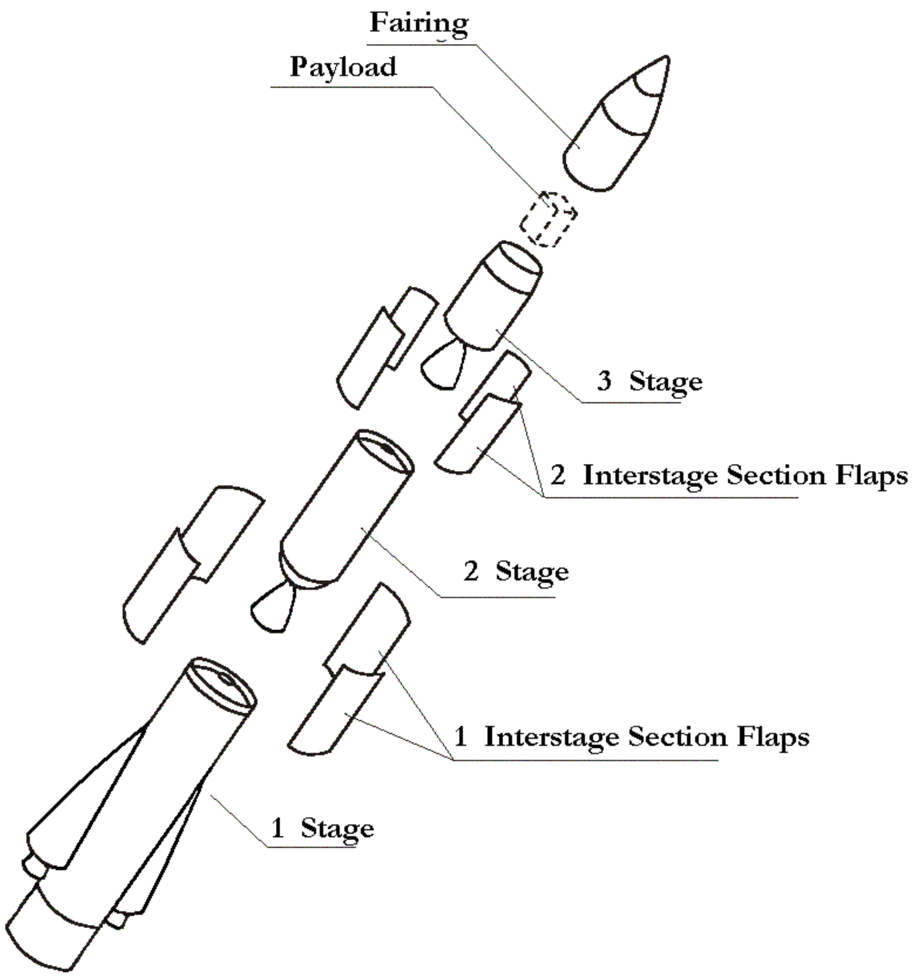

Figure 13 – Overview of 3 stages launch system

Each stage of a vehicle is made up of three basic subsystems. These are as follows:

- Propulsion;
- Structure;
- Guidance, navigation and control.

In addition to the components that make up each stage, the vehicle as a whole might also have a fairing in which to carry and protect its payload.

In a non-limitative manner, for what concerns the propulsion, specifically for this study, the selected launch vehicle to which the X-FAST take-off auxiliary device is applied shall employ at least a propulsion system making use of at least one liquid propellant. In particular, for this study, the attention is oriented to such types of vehicles and only storable liquid fuelled systems are considered. To such vehicle the X-FAST device is applied, in particular, to the first stage.

To mention it, the structures of launch vehicles principally are tanks, plumbing and engines. The structure subsystem can be re-dimensioned for the first stage, to which the X-FAST technology is mainly applied.

The final element of a launch vehicle is the guidance and control system. This is the launch vehicle's intelligence. The system tells the engines when to fire and for how long, initiates stage separation, can sense a fatal problem with the launch, and can initiate a self-destruction sequence.

The fairing is used to protect the payload before and during the launch and while crossing the lower levels of the atmosphere.

For what concerns the preliminary assessment of the performances, at this level of study, in which it is of interest to prove and validate the X-FAST technology advantages when in use, the guidance and control subsystems are supposed ideal and able to realise an appropriate control [(38) – *H.S. Seifert*, *K. Brown*, 1961], [(39) – *R. Biesbroek*, *B. Ancarola*, 2002].

On the other hand, in order to assess the eventual gaps from the effectively desired motion, a wide analysis has been performed showing that, under proper dimensioning and design assumptions, the employment of the X-FAST auxiliary device onboard typical industrial rockets allows for an increase in the dynamic stability issues. This is due to the fact that, during the vertical ascent, the intrinsic dynamics of the vehicle's body require a lower effort to be exerted by the TVC with respect to a conventional comparative vehicle. Further details can be found in the literature developed in the frame of the wider X-FAST research project [(4) – *AB Technologies*, 2005].

Furthermore, to describe vehicle's motion and performances it is fundamental to characterise the other two remaining subsystems, of which each stage is made up, especially because of the remarkable impact on them introduced by the application of the X-FAST concept.

Indeed, according to the chosen mission strategy (see the previous paragraph), a reduction in the required amount of overall structural and propellant mass can be expected. The following figure qualitatively compares a conventional system and one employing an X-FAST take-off auxiliary device by breaking out their gross weight in terms of percent to structure, propellant and upper stages [(40) – *E.F. Bruhn*, 1967].

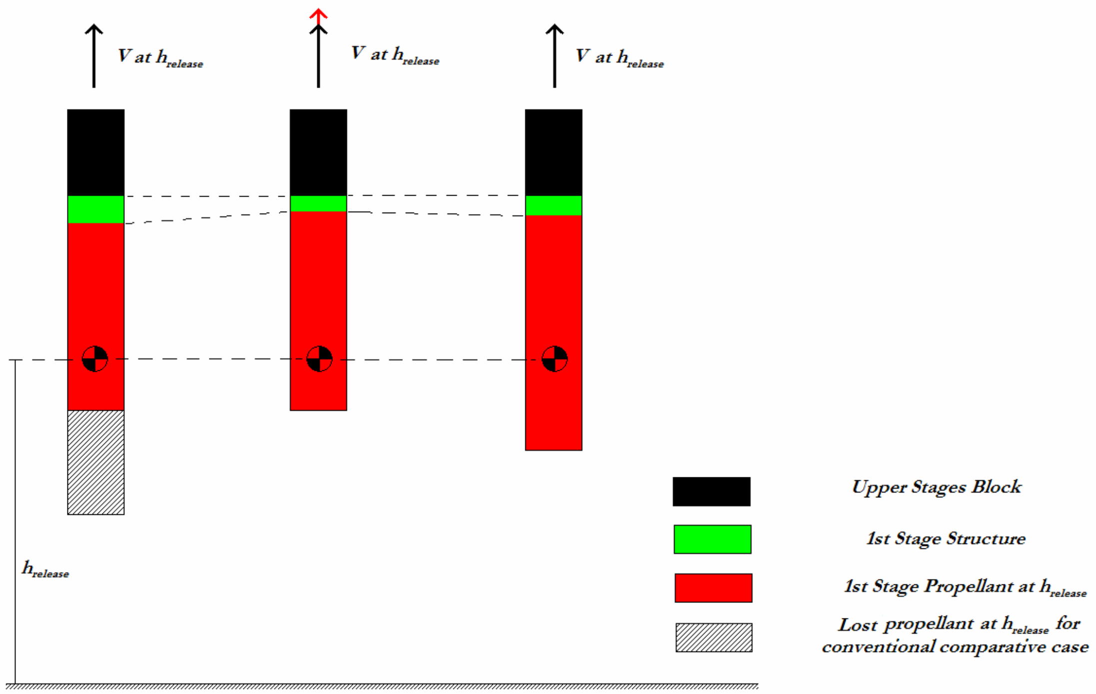

Figure 14 – Qualitative comparison between a conventional vehicle and a vehicle employing an X-FAST system versus first and second strategy, in terms of their gross weight.

In the following figure it is instead represented, in a qualitative manner, the same reduction applied on a reference case, such as Ariane 40.

Figure 15 – Ariane 40 comparisons versus first and second strategy

The main parameters of a launch vehicle's stage are: structural mass; propellant mass (or, fixed the technology, structure to propellant ratio once one of the two masses is known); geometric features and/or shape factor (such as frontal surface area and length).

Moreover, it is essential to give the main features about the engines. In particular: mass flow rate, specific impulse, exit pressure, exit area, and number of engines. If necessary, the nominal payload and fairing mass shall be supplied.

For the definition of the mathematical model the configuration of a launch vehicle can be summarised with a set of parameters such as the ones reported in the following table.

Parameter	Description	Unit
$m_{structural}^{Stage(i)}$	Structural Mass of the i-*th* Conventional Stage	[kg]
$m_{\Pr opellant}^{Stage(i)}$	Propellant Mass of the i-*th* Conventional Stage	[kg]
$m_{structural\_Stage1}^{X-FAST}$	Structural Mass of the X-FAST First Stage	[kg]
$m_{\Pr opellant\_Stage1}^{X-FAST}$	Propellant Mass of the First X-FAST Stage	[kg]
A_{front}	Frontal Surface Area of the Launch Vehicle	[m^2]
$\dot{m}^{Stage(i)}$	Mass Flow rate of the Engines of the i-*th* Stage	[kg/s]
$I_{Sp}^{Stage(i)}$	Specific Impulse of the Engines of the i-*th* Stage	[s]
$p_{e}^{Stage(i)}$	Outlet Nozzle Pressure of the i-*th* Stage Engines	[Pa]
$A_{e}^{Stage(i)}$	Output Nozzle Area of the i-*th* Stage Engines	[m^2]
$n_{Engines}^{Stage(i)}$	Number of Engines of the i-*th* Stage	[-]
$m_{Payload}$	Nominal Payload Mass	[kg]
$m_{Fairing}$	Fairing Mass	[kg]

Table 1 – Parameters for the configuration of the launch vehicle

4.4 EQUATIONS OF MOTION

The mathematical model considered in order to describe the motion of the centre of mass of the vehicle's body, for the part of the flight during which the X-FAST concept is employed, follows a Newtonian approach, according to the second law of dynamics, applied to a point mass. It can be formally stated, in terms of equations, as follows:

$$m(t)\frac{d^2P}{dt^2} = \underline{F}(t, P, \dot{P}, \ddot{P}) \qquad \text{Eq. 11}$$

where $m(t)$ is the mass of the vehicle's body, which for conventional rockets and in general is a variable function of the time, since the vehicle ejects the propellant; *P*, $\dot{P}$ and $\ddot{P}$ respectively represent the position, the velocity and the acceleration of the centre of mass of the vehicle's body and $\underline{F}(t, P, \dot{P}, \ddot{P})$ is the integral of the applied external forces acting on the vehicle's body.

In order to mathematically characterise in the previous expression the concept applied, it is necessary to identify the forces acting on the vehicle's body.

However, first of all, it has to be noticed that the X-FAST system (vehicle's body and pipe together) can be schematised as a point-mass concentrated in the vehicle's body centre of mass and with total mass equal to the vehicle's body mass, on which the existing external forces are applied. For what concerns the determination of the motion of the vehicle, according to standard arguments in mechanics [(41) – *A. D'Anna*, *P. Renno*, 1991], [(42) – *A. Maio*, 1997] the presence of an externally mechanically connected body (the pipe) can be rationally schematised through the conceptual elimination of it and through the application of the corresponding force ($\underline{F}_{Pipe}$) acting on the vehicle.

A rational scheme of the applied forces is shown in the following figure, where the generic vehicle is also represented in order to visualise the physics of the problem.

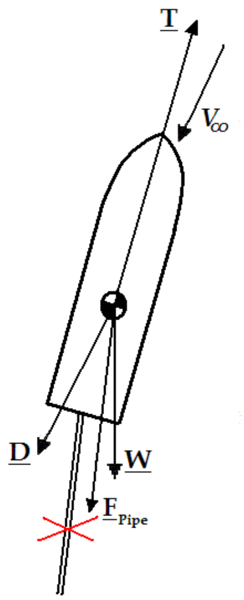

Figure 16 – Rational scheme of the applied forces for a point mass description.

The acting forces to be taken into account for the determination of the translation of the centre of mass of the vehicle's body are: thrust force, aerodynamic-drag force and weight of the body, plus an additional force introduced by the presence of an external system needed to feed the vehicle during the first part of the flight.

The previous equation can be particularised as follows:

$$\underline{T} + \underline{D}_{Body} + \underline{W}_{Body} + \underline{F}_{pipe} = m(t)\frac{d^2 P}{dt^2} \qquad \text{Eq. 12}$$

where: $\underline{T}$ is the thrust force offered by the engines; $\underline{D}_{Body}$ is the aerodynamic drag force of the vehicle's body flying through the atmosphere; $\underline{W}_{Body}$ is the weight of the vehicle's body always pointing in the direction of the Earth's centre; $\underline{F}_{pipe}$ is the additional force introduced by the presence of the external system.

In particular, for what concerns the additional force $\underline{F}_{pipe}$, it is the result of some terms due to the interaction with the external atmosphere and due to the interaction with the internal viscous fluid that flows through the propellant transfer system. For the determination of the value of $\underline{F}_{pipe}$, it has also to be considered that the mechanical problem is the one of a body which is evolving in time and in length as the vehicle's body ascends gaining altitude and speed, as shown in details in the X-FAST engineering model (see paragraph 4.9).

According to the previous assumption, the algebraic vector expression can be formulated as follows:

$$\underline{F}_{Pipe} = \underline{F}_{\tau_{Pipe}^{Int}} + \underline{F}_{\underline{\tau}_{Pipe}^{Ext}} + \underline{F}_{\underline{\sigma}_{Pipe}^{Axial}} + \underline{D}_{Pipe} \qquad \text{Eq. 13}$$

where: $\underline{F}_{\underline{\sigma}_{Pipe}^{Axial}}$ is the axial traction force that the pipe imposes on the vehicle's body; $\underline{F}_{\underline{\tau}_{Pipe}^{Ext}}$ is the skin friction integral force due to the fact that the pipe is in motion with the vehicle in presence of an atmosphere externally interacting with it (viscous external drag effect); $\underline{F}_{\tau_{Pipe}^{Int}}$ is the skin friction integral force due to the fact that, along the umbilical tube, there is the internal flow of propellant pumped towards the vehicle (viscous internal sustaining-lifting effect); and $\underline{D}_{Pipe}$ is the aerodynamic drag of the pipe due to the atmosphere interacting with the pipe in the normal direction.

In particular, $\underline{F}_{\underline{\tau}_{Pipe}^{Ext}}$ is a viscous drag arising from the tangential shear (skin friction) acting on the surface by virtue of viscosity; on the other hand the $\underline{D}_{Pipe}$ of the umbilical tube is a shape pressure drag arising from the pressure forces acting normal to the tube's surface.

Substituting the expression of $\underline{F}_{Pipe}$ in Newton's law of motion, it becomes:

$$\underline{T} + \underline{D}_{Body} + \underline{W}_{Body} + \underline{D}_{Pipe} + \underline{F}_{\tau_{Pipe}^{Int}} + \underline{F}_{\underline{\tau}_{Pipe}^{Ext}} + \underline{F}_{\underline{\sigma}_{Pipe}^{Axial}} = m(t)\frac{d^2 P}{dt^2} \qquad \text{Eq. 14}$$

where the sum is an algebraic sum and the signs of each force are contained in the vector components.

4.5 VERTICAL ASCENT MODEL

According to the analysis to be performed a vertical motion hypothesis is applied for what concerns the part of the flight during which the hose is attached to the vehicle's body. The vehicle is considered in ascent moving without any manoeuvre.

It is important to notice that such hypothesis is sufficient and exhaustive to describe the motion of the vehicle employing the X-FAST system in the considered phase of the flight and to obtain an understanding on the gain of the application of the X-FAST technology [(38) – *H.S. Seifert*, *K. Brown*, 1961].

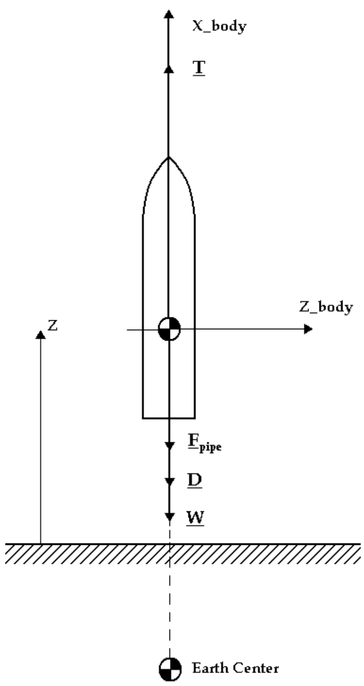

Figure 17 – Vertical ascent scheme

Under such hypothesis, the existing applied external forces are all directed along the longitudinal axis of the vehicle (X_{Body}) that, for the type of motion considered, points towards the centre of the Earth, independently from the adopted Earth model (flat or oblate). In particular, the pipe is considered connected to the vehicle's body in such way that F_{pipe} acts along the axial-body direction [(43) – *ANSI*, 1992]. This means that the only motion allowed to the hose is vertical and along its longitudinal axis.

Projecting along the vertical direction, the vector equation of motion becomes:

$$\frac{d^2 z_{CM}(t)}{dt^2} = \frac{1}{m(t)}\left[T - |W| - |D| + F_{pipe}\right] \qquad \text{Eq. 15.a}$$

where:

$$F_{pipe} = -F_{\sigma_{Pipe}^{Axial}} + F_{\tau_{Pipe}^{Int}} - F_{\tau_{Pipe}^{Ext}} - D_{Pipe} \qquad \text{Eq. 16}$$

In particular, for typical flight ranges of interest, D_{Pipe} becomes negligible under the considered configuration hypothesis, mainly because no normal components of the asymptotic velocity of the air are present. Depending on the ranges of application, the term $F_{\tau_{Pipe}^{Ext}}$ can be become negligible because of the lower order of magnitude with respect to the other terms of the equation.

The motion of the vehicle can be evaluated solving the Cauchy problem defined by the previous equation under the following initial conditions:

$$\begin{cases} z(t=0) = h_0 = 0 & [\text{m}] \\ \dot{z}(t=0) = V_0 = 0 & [\text{m/s}] \end{cases} \qquad \text{Eq. 15.b}$$

The terms of the equations of motion introduced by the employment of the X-FAST concept are explained, in more details, in the paragraph related to the X-FAST engineering model.

After X-FAST system release the motion of the vehicle's body becomes the one of a fully conventional system and consolidated arguments in flight mechanics for launchers can be considered [(38) – *H.S. Seifert*, *K. Brown*, 1961], [(44) – *J.F. White*, 1961], [(39) – *R. Biesbroek*, *B. Ancarola*, 2002], [(17) – *B. Ancarola*, 2002].

4.6 ENVIRONMENT MODEL

The environment, in which the vehicle is located, is essentially schematised considering the presence of:

- Earth;
- Atmosphere.

No wind is considered to be present during the X-FAST flight phase. A brief overview is given in the following paragraphs.

4.6.1 EARTH MODEL

The Earth's gravity force due to the Earth's gravitational potential (i.e. the geo-potential) can be modelled using a geo-potential model. The Earth's gravitational field is predominately that of a solid sphere of mass. However, the Earth is not a sphere, thus the perturbations in the geo-potential due to the non-spherical Earth must be considered when necessary.

Considering the effect of a spherical Earth, it can be assumed to be a point mass located at its centre. Given two masses, M and m, separated by a vector distance, $\underline{r}$ (which has a magnitude of r), the attractive force, $\underline{F}$ of the two masses is given by:

$$\underline{F}_g = -\frac{GMm}{r^3}\underline{r} \qquad \text{Eq. 17}$$

where G is the gravitational constant. A gravitational potential function, U, of the Earth is defined by:

$$U = \frac{\mu_E}{r} \qquad \text{Eq. 18}$$

where μ_E is the gravitational parameter of the Earth ($3.986 \cdot 10^{14}$ [m^3/s^2]), which is the mass of the Earth, M_E times the gravitational constant, G. Note that the gravitational potential function is defined in this case for a point mass (i.e. spherical Earth). Combining the two previous equations follows:

$$\underline{F}_g = -m\underline{\nabla}U \qquad \text{Eq. 19}$$

where $\underline{\nabla}$ is the gradient operator. Applying Newton's law, the gravitational acceleration, $\underline{a}_g$, can be given as:

$$\underline{a}_g = -\underline{\nabla} U \qquad \text{Eq. 20}$$

The "two-body" gravitational acceleration due to the presence of the Earth is calculated using the previous equations.

The non-spherical perturbation of the geo-potential acceleration can be modelled in several ways. The most commonly used model for spacecraft orbits is the spherical harmonic expansion. The Earth's gravitation potential function is expressed as a summation of terms that are a function of the position of the spacecraft. The spherical harmonic expansion can be derived by expressing the potential function, *U*, as a sum of the potential due to infinitesimal point masses over the Earth's volume. A thorough derivation can be found in [(45) – *D.A. Vallado*, 1997]. The result of the derivation yields the potential function for a non-spherical Earth:

$$U = \frac{\mu_E}{r} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \left(\frac{R_E}{r} \right)^l P_{lm}[\sin(\phi)] \left\{ C_{lm} \cos(m\lambda) + S_{lm} \sin(m\lambda) \right\} \qquad \text{Eq. 21}$$

where: $P_{lm}[\sin(\phi)]$ are the associated Legendre functions (see the annex); C_{lm} and S_{lm} are gravitational coefficients; R_E is the mean equatorial radius of the Earth; ϕ, λ and r are the co-ordinates of the spacecraft in the spherical co-ordinate system. The summation index, *m*, represents the order of the geo-potential scheme, while the index, *l*, represents the degree of the scheme.

If the co-ordinate system is centred at the Earth's centre of mass, the coefficients C_{10}, C_{11}, and S_{10} are all zero. The 0th term is the spherical Earth term. Thus, the previous equation can be written in a more commonly used form as follows:

$$U = \frac{\mu_E}{r} \left[1 + \sum_{l=2}^{\infty} \sum_{m=0}^{l} \left(\frac{R_E}{r} \right)^l P_{lm}[\sin(\phi)] \left\{ C_{lm} \cos(m\lambda) + S_{lm} \sin(m\lambda) \right\} \right] \qquad \text{Eq. 22}$$

The double-summation term in this equation is used to calculate the perturbation of the gravitational acceleration due to the non-spherical nature of the Earth. As with the two-body acceleration, the perturbation acceleration is found by taking the gradient of the potential function [(46) – *J.R. Vetter*, *Et al.*,1993], [(47) – *D.J. Fonte*, *Et al.*, 1993], [(48) – *J. A. Marshall* , 1988].

4.6.1.1 WGS-84 AND SIMPLIFIED MODEL

When a very accurate modelling and description of the motion of the vehicle is wanted the World Geodetic System 1984 (WGS-84) can be employed as the model to describe the shape of the Earth.

The WGS 84 is an Earth fixed global reference frame, including an oblate Earth model. It is defined by a set of primary and secondary parameters, as the following table shows.

Parameter	Description	Value	Unit
μ_E	Gravity Constant	$3.986004418 \cdot 10^{14}$	[m^3/s^2]
a	Equatorial Radius	6378137	[m]
c	Polar Radius	6356752.3	[m]
ω	Rotation Rate	$7.292115 \cdot 10^{-5}$	[rad/s]
f	Flattening	1/298.257223560 (f= (a-c)/a)	[-]
J_2	Dynamic Form Factor	$1.081874 \cdot 10^{-3}$	[-]
θ_g	Geographic latitude	-	[rad]
θ	Geocentric latitude	-	[rad]

Table 2– WGS Parameters

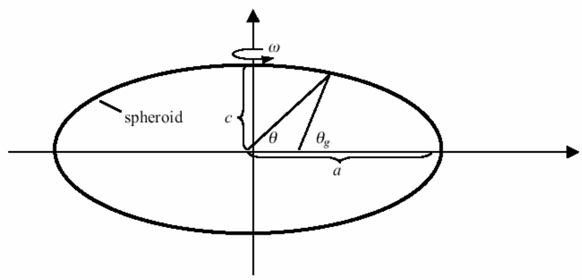

Figure 18 – Earth Spheroid, WGS-84

The primary parameters define the shape of an Earth ellipsoid, its angular velocity, and the Earth mass, which is included in the ellipsoid reference; the secondary parameters define a detailed gravity model of the Earth [(49) – *Department of Defence*, 1984].

In case the motion of the vehicle can be mainly schematised as a vertical ascent and the range of variation of the altitude remains limited, the WGS-84 model is not necessary to describe the motion, as the variation of gravity remains very narrow.

For such case a flat model of the Earth together with a constant value of the gravity acceleration can be employed giving very satisfactory information of the motion of the vehicle [(38) – *H.S. Seifert*, *K. Brown*, 1961].

4.6.2 ATMOSPHERIC MODEL

The adopted atmospheric model is the U.S. Standard Atmosphere. This model is an idealised representation of the conditions considered typical for middle latitudes. It was developed because of the need to define a reference atmosphere for use in the design of aircraft and missiles and the instruments used on them.

Based on rocket and satellite data and perfect gas theory, the atmospheric densities and temperatures are represented from sea level to 1000 [km]. The U.S. Standard Atmospheres 1958, 1962, and 1976 consist of single profiles representing the idealised, steady state atmosphere for moderate solar activity.

The parameters listed include temperature, pressure, density, acceleration caused by gravity, pressure scale height, number density, mean particle speed, mean collision frequency, mean free path, mean molecular weight, sound speed, dynamic viscosity, kinematics viscosity, thermal conductivity, and geo-potential altitude.

The altitude resolution varies from 0.05 [km] at low altitudes to 5 [km] at high altitudes [(50) – *R.A. Minzner*, 1959], [(51) – *SAE Aerospace,* 1969], [(52) – *Smith*, *Et al.*, 1982], [(53) – *A. S. Jursa*, 1985].

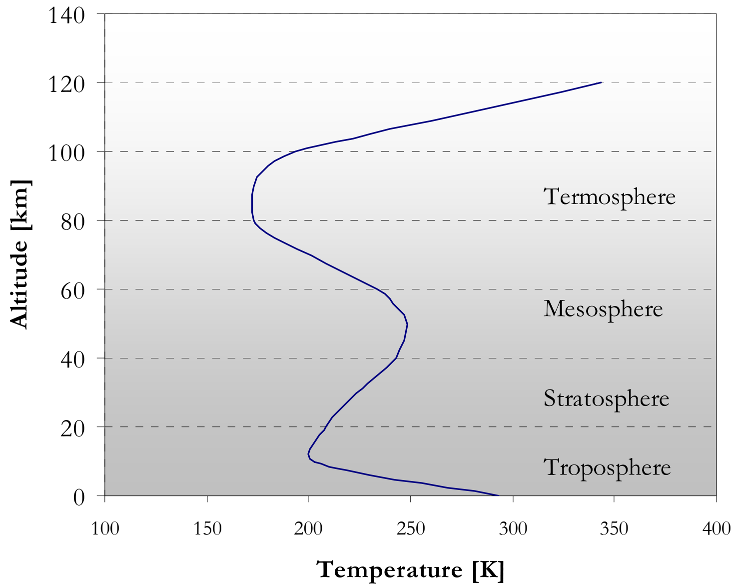

Figure 19 – Atmosphere layers: altitude versus temperature

The air is assumed to obey the perfect gas law and the hydrostatic equation, which, taken together, relate temperature, pressure, and density variations in the vertical direction. It is further assumed that the air contains no water vapour and that the gravity acceleration does not change with height.

This last assumption is tantamount to adopting a particular unit of geo-potential height in place of a unit of geometric height for representing the measure of vertical displacement, because the two units are numerically equivalent in both the metric and English systems, as defined in connection with the standard atmosphere.

The current standard atmosphere is the one adopted in 1976 and is a slight modification of the one adopted in 1952 by the International Civil Aeronautical Organisation (ICAO), which, in turn, supplanted the NACA Standard Atmosphere (or U.S. Standard Atmosphere) prepared in 1925. It assumes sea level values as follows [(54) – *COESA*, 1976]:

- Temperature: 288.15 [K];
- Ice melting point at one standard atmosphere pressure: 273.16 [K];
- Pressure: 101325 [Pa];
- Density: 1225 [g/m^3];
- Mean molar mass: 28.964 [g/mole];
- Pressure altitude of the tropopause: 11 [km];
- Temperature at the tropopause: -56.5[°C].

The following figures show the atmospheric properties of the 1976 Standard Atmosphere as function of the altitude in SI units.

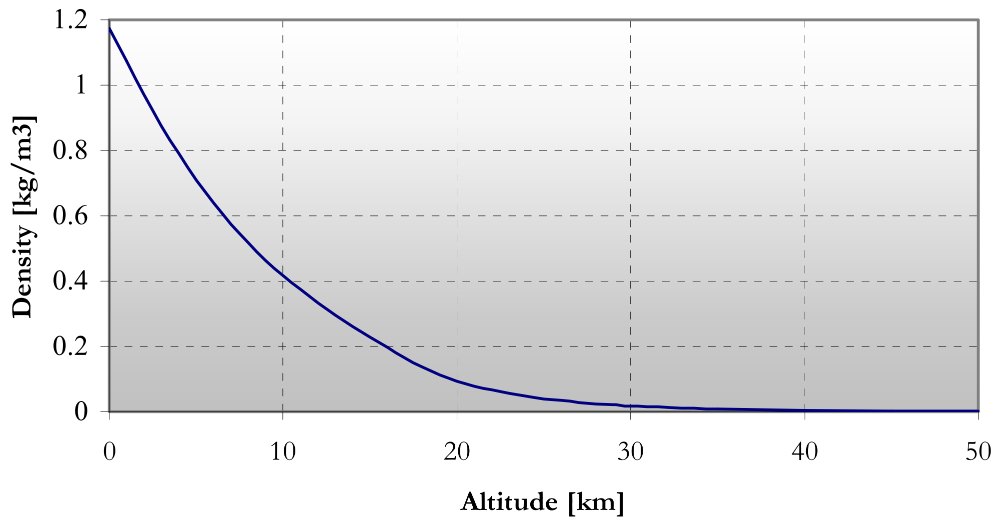

Figure 20 – Air density versus altitude

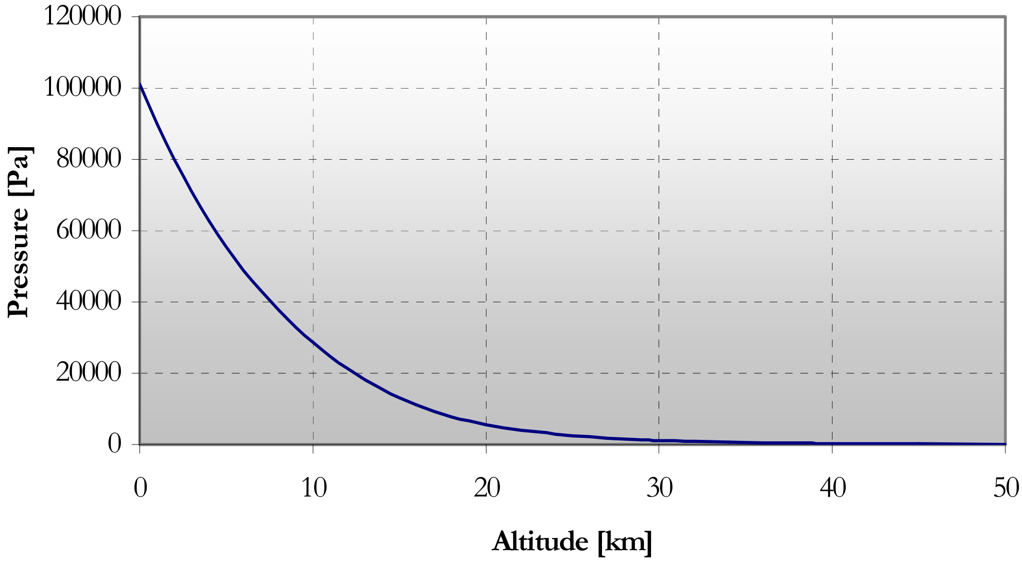

Figure 21 – Ambient pressure versus altitude

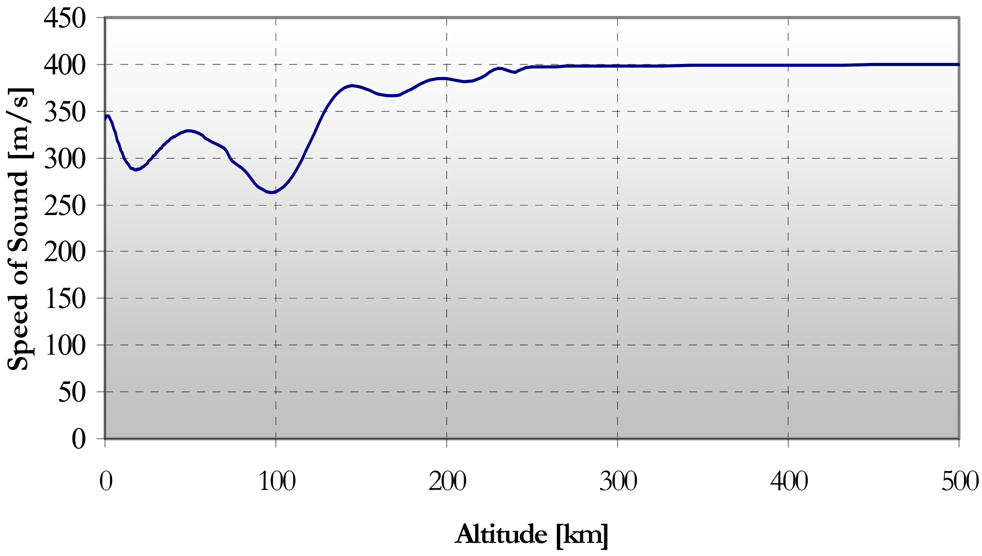

Figure 22 – Speed of sound versus altitude

4.7 AERODYNAMIC MODEL OF THE VEHICLE

As a launcher flies through the atmosphere, it experiences aerodynamic forces and moments. These forces (lift and drag) may be classified into two general types:

- Those due to air friction;
- Those due to pressure/shape.

The former type, only drag, is generated by the shearing action of the air due to its viscosity and the latter by differences in surface pressures which result in the creation of both lift and drag forces.

In details, the drag arising from the pressure forces acting normal to the vehicle surface is known as pressure drag, and the one arising from the tangential forces of skin friction acting on the surface by virtue of viscosity is called viscous drag or skin friction [(27) – *L.G. Napolitano*, 1969], [(55) – *R. Monti*, *R. Savino*, 1998], [(56) – *J.N. Nielsen*, 1960].

The drag due to pressure *p* at the vehicle surface is:

$$D_p = -\iint_{S_m} p\cos(n, V_0)dS_m \,, \qquad \text{Eq. 23}$$

where: V_0 is the asymptotic velocity; $\cos(n,V_0)$ is the cosine of the angle between V_0 and the outward normal to the vehicle surface. The surface S_m comprises the total area of the vehicle.

If τ is the local skin friction per unit area due to viscosity, then the viscous drag is:

$$D_v = \iint_{S_m} \tau \; \cos(\mathrm{t}, \mathrm{V}_0)\; \mathrm{dS_m} \,, \qquad \text{Eq. 24}$$

where $\cos(t,V_0)$ is the cosine of the angle between V_0 and the tangent to the vehicle surface in the τ direction. Note that t and τ are in the same direction.

Fixed the body geometry and the angle of attack, the axial aerodynamic force coefficient C_D depends on the Mach and Reynolds numbers [(57) – *J.D. Anderson*, 2001].

Without any loss in generality, for typical launch vehicles, a simplified but still accurate model is adopted to describe its aerodynamic features and the relative importance of the aerodynamic effects with reference to the others [(58) – *S.S. Chin*, 1961], [(44) – *J.F. White*, 1961].

Such model supposes that no lift is considered applied at the vehicle $(C_L = 0)$ and no derivative data are supplied $\left(\frac{\partial C_L}{\partial \alpha}(M) = 0\right)$. The aerodynamic force can be computed, in the wind reference frame, as:

$$F_{Aerodynamic} = -qA_{ref}C_D(M)\,, \qquad \text{Eq. 25}$$

where: M is the Mach number; q the dynamic pressure; A_{ref} the aerodynamic reference area.

The data related to the axial drag force coefficient are to be provided as a function of the Mach number and typically in tabular format.

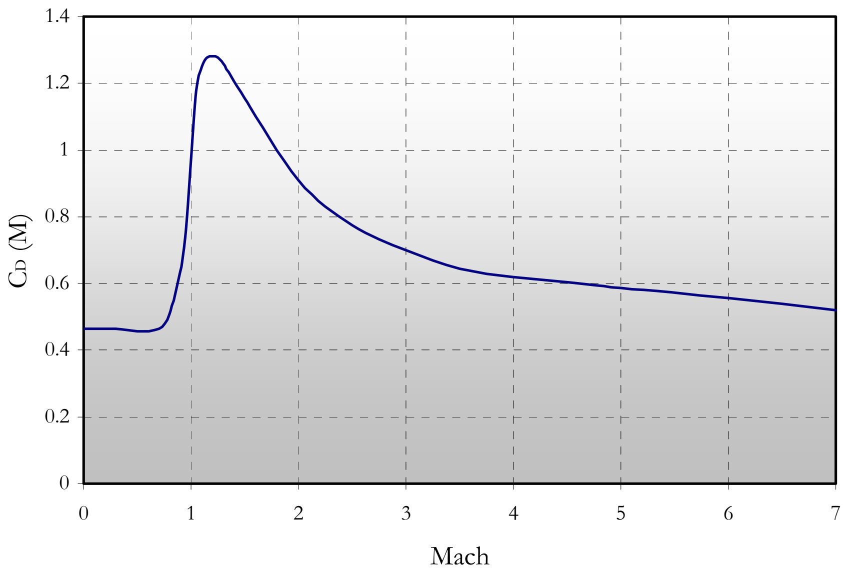

Figure 23 – Typical drag force coefficient as a function of the Mach number

The expression applied to evaluate the aerodynamic force in the body reference frame is specified as follows:

$$D_{Body} = \frac{1}{2}\rho_{air}V_{Rel}^2 A_{front}C_D(M) \qquad \text{Eq. 26}$$

where: ρ_{air} is the air density; V_{Rel} is the relative velocity of the vehicle's body with respect to the air; A_{front} is the body frontal surface area; $C_D(M)$ is the axial drag aerodynamic coefficient.

4.8 PROPULSION MODEL

For what concerns the cases of interest for this study (vehicles designed as a single body launcher, with some liquid propelled stages [1, 2 or 3] disposed in series), the propulsion system of each stage is considered as a cluster of one or several engines of the same type.

The amount of thrust generated depends on the mass flowing through the engine per unit of time, $\dot{m}$, and the equivalent exit velocity, c, of the exhaust gas produced by the combustion chamber and accelerated through the nozzle, evaluated as:

$$c = I_{sp} \cdot g_0 \,, \qquad \text{Eq. 27}$$

where: I_{sp} is the specific impulse; g_0 is the gravity acceleration at the sea level.

Defined V_e and p_e respectively as the exit velocity and pressure and p_a as the ambient pressure, the thrust scalar equation is written as follows:

$$T = \dot{m} \cdot V_e + (p_e - p_a) A_e \qquad \text{Eq. 28}$$

and it is computed along the x-body axis which is the longitudinal symmetric axis of the nozzle [(2) – *A. Russo Sorge*, 1984].

The model applies to typical liquid rocket motors with a fixed mass flow rate profile and fixed burn duration. Total propellant mass, structural mass and overall burn duration are to be specified. In particular, for what concerns the initial propellant and the structural mass, they must be specified on the base of the considerations and evaluations performed by the application of the X-FAST concept, according to the arguments presented in paragraph 4.2.

The mass flow rate ($\dot{m}$) and specific impulse (I_{sp}), used to evaluate the exit velocity, are specific properties of each stage's engines. In particular their magnitude depends on the design of the nozzle and on the selection of the propellants.

The mass flow versus time law, which is typically given in tabular format, might be used for the description of the model, and this option works in such way that the integral of the mass flow rate approximation, with respect to the time, is exactly equal to the specified total propellant mass. However, a different choice is taken to approach the problem in a generic manner from the theoretical point of view, since during the design phases the time variation of the experimental parameters cannot be pointwise predicted in detail or because the experimental results are often available as average values. Hence, from now on the mass flow rate is supposed to be constant and equal to the average mass flow rate in time, defined as follows:

$$\dot{m} = \tilde{\dot{m}} = \frac{1}{\Delta t}\int_{\Delta t} \dot{m}(t)dt \,, \qquad \text{Eq. 29}$$

where Δt is the duration of the considered vehicle stage, evaluated as follows:

$$\Delta t = \frac{m_{\Pr opellant}}{\dot{m}_{\Pr opellant}} \qquad \text{Eq. 30}$$

The configurable parameters for each stage are: $\dot{m}_i$, I_{sp_i}, n_i, p_{e_i}, A_{e_i} $\quad \forall i = 1,2,...,n$.

4.9 X-FAST ENGINEERING MODEL

According to the arguments presented in the previous paragraphs, the reader can notice that the main and fundamental engineering features and characteristics introduced by the X-FAST technology are the ones related to the employment of an externally connected propellant transfer system linked to a ground infrastructure, at the base edge, and to the body of an ascending vehicle at the top edge.

For the estimation and the design of the vertical ascent the analyst is in need of knowing certain intrinsic parameters and their pointwise value in order to have a comprehension of the magnitude of the physical phenomena involved.

At system level such parameters of interest can be identified in the ones related to the tension and traction forces, (in particular the ones determined at the top edge of the propellant transfer system); the cross section diameter/radius and thickness dependency with respect to the rectified co-ordinate; the shear stress acting on the internal wall of the propellant transfer system due to the viscous interaction between the inner propellant flow and the hose; the pressure gap between the base and the top fronts of the propellant flowing through the hose, due to the difference in altitude and to viscous intrinsic phenomena; the hydraulic power to be supplied by the ground based pumping systems, in order to allow a fluid propellant to follow and reach an ascending body; the sustaining lifting effect acting at the wall of the propellant transfer system, as a consequence of an integral effect of the shear.

The identification of such parameters and their time dependence is of help for the designer in order to define the system configuration.

In the following sections a description of the previously mentioned parameters and their scope of utilisation are given.

4.9.1 TENSION AND TRACTION

The tension that instantaneously is established in the material cross section of the propellant transfer system, along its axial direction, is caused by the mechanical connection of the top edge to an ascending-accelerating body (the vehicle), by its weight and by its intrinsic acceleration.

The need to know the intensity and the magnitude of the axial tension is fundamental when the material selection has to be carried out and when the mechanic and shape dimensioning has to be performed. It has to be noticed that the values of the axial tension, once fixed a specific cross section of the hose, is a variable function of the time. This is directly related to the fact that the hose can be considered as a body, which is continuously evolving in time and with a rectified length that increases as the vehicle's body departs and gains altitude.

According to previous work and assessments [(11) – *B. Ancarola*, 2003], [(10) – *B. Ancarola*, *L. Deseri*, 2003], [(18) – *L.D. Landau*, *E.M. Lifshitz*, 1970], [(24) – *S.P. Timoshenko*, *J.N. Goodier*, 1970] the expression of the axial tension, which acts in the vertical direction of the flight, evaluated at the connection point between the vehicle's body and the top edge of the hose can be evaluated as follows:

$$\left|\sigma_z\right|_{\xi=\xi_{c.p.}} = \left|\rho_{mat}\left[g+\ddot{z}_{cm}\right]\cdot z_{cm}\right| \qquad \text{Eq. 31}$$

Where ρ_{mat} is the density of the material selected for the hose, g is the gravity acceleration, $\ddot{z}_{cm}$ and z_{cm} are respectively the acceleration and the altitude of the centre of mass of the vehicle's body. In particular this is obtained in the case for which the hose shape is not function of the rectified co-ordinate $\left(\frac{\partial}{\partial\xi}\equiv 0\right)$.

While the tension is necessary to dimension the hose, the traction force measured at the top edge of the hose is needed to design the flight and to have an understanding of the influence of the presence of the external system on the flight dynamics parameters. Considering the previous equation and taking into account the phenomena that relate traction force to stress, the following equation can be stated:

$$F_{traction,z} = -\sigma_z\big|_{\xi=\xi_{c.p.}} A_{sect} = -\rho_{mat}\left[g + \ddot{z}_{cm}\right] z_{cm} A_{sect}\,, \qquad \text{Eq. 32}$$

where A_{sect} is the cross section area of the hose.

In the particular case of a circular shaped cross-section of the hose the previous expression becomes:

$$F_{traction,z} = -\sigma_z\big|_{\xi=\xi_{c.p.}} \pi\left(R_{ext}^2 - R_{in}^2\right) = -\pi\ \rho_{mat}\left[g + \ddot{z}_{cm}\right]\ \left(2R_{in} + s\right) s\ z_{cm} \qquad \text{Eq. 33}$$

where the terms R_{in}, R_{ext} and s are respectively the inner radius, the external radius and the thickness of the hose. Again, the assumption is made that the radius and the thickness of the hose are constant functions of the rectified co-ordinate.

It can be noticed that the dependence of the tension and of the traction force with respect to the time can be expected to be parabolic/quadratic, especially in the case that the acceleration of the vehicle's body does not vary too rapidly or, in other words, if its variation is very close to its average value from lift-off to hose release.

This is true when the time variation is relatively short [(12) – *V. Ferone*, 1996]. However, this is the case according if state of the art conventional systems are considered [(14) – *S.J. Isakowitz*, 1999], [(15) – *Arianespace*, 1999], [(17) – *B. Ancarola*, 2002].

The following graphs show the qualitative behaviour of σ_ξ at the connection point between vehicle's body and hose and $F_{traction,z}$ as functions of time.

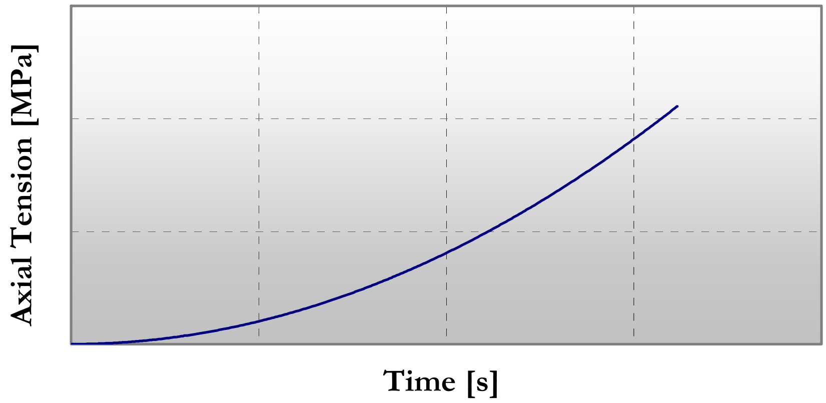

Figure 24 – Qualitative view of the axial tension versus time

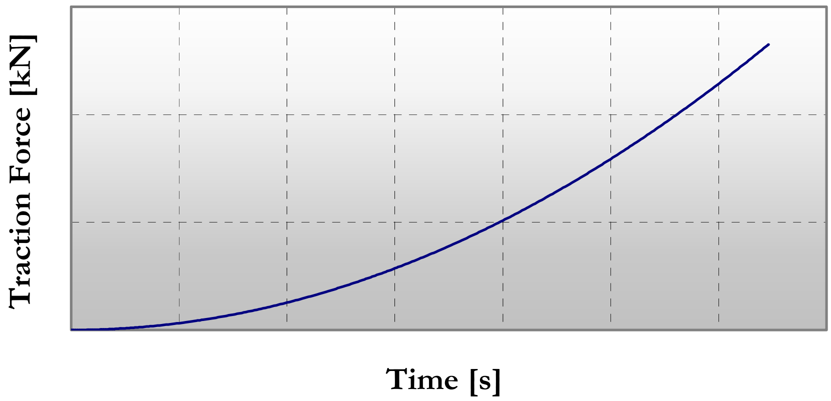

Figure 25 – Qualitative view of the traction force versus time

4.9.2 PROPELLANT TRANSFER SYSTEM: VARIABLE SECTION AND THICKNESS

As far as the definition of the shape is concerned, the designer can notice that, when defining the geometrical configuration of the propellant transfer system, various degrees of freedom maybe left to discretion. Indeed one can think about designing the hose in such way that, when the whole of it is fully deployed, its inner radius and thickness are variable functions of the rectified co-ordinate and of the azimuth.

In particular, stating that the inner radius depends locally on the azimuth is equivalent to state that the cross section is not constrained to be circular.

For example, supposed the inner radius as a constant function of azimuth and rectified co-ordinate, one can think of the case of having a degree of freedom on the design of the thickness as a function of the only rectified co-ordinate; the clear advantage of the intuition stands in the fact that, if considered a hose with constant thickness and inner radius, any possible other hose inscribed in it has a lower volume so, fixed the density, lower mass.

Hence, if the shape of the hose is properly selected, it is possible to recursively shape the time dependence of the traction force according to the required needs (thus even lowering the peak and the average).

This intuition is even more justified if it is considered that, at the aim of dimensioning the hose for circumferential loads, the thickness can be higher where the pressure of the internal flow is higher; lower where the pressure is locally lower [(4) – *AB Technologies*, 2004], [(10) – *B. Ancarola*, *L. Deseri*, 2003]. In particular, the equation for the pointwise evaluation of the axial traction force can be more generalised as follows [(59) – *V. Ferone*, 1997]:

$$F_{traction,z} = -\rho_{mat}\left[g + \ddot{z}_{cm}\right]\int_0^{2\pi}\int_{R_{in}[\xi(t)]}^{R_{ext}[\xi(t)]}\int_0^{z_{CM}(t)} R[\xi(t)]\,d\vartheta\, dR\, d\xi \qquad \text{Eq. 34}$$

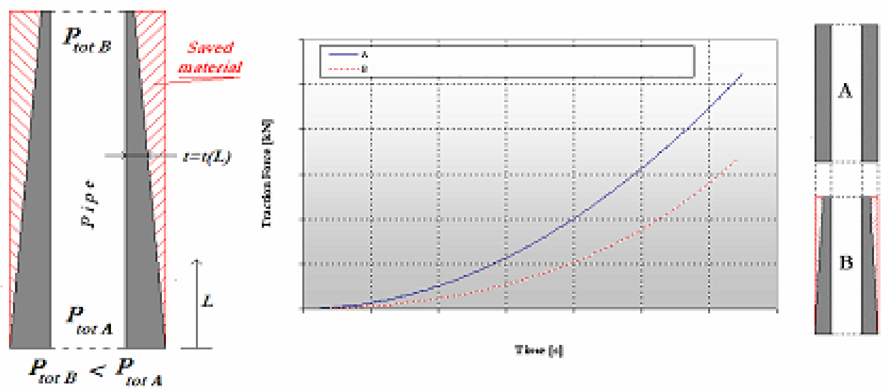

Figure 26 – Qualitative comparison between the traction forces versus time for constant (A) and variable (B) thickness

4.9.3 PROPELLANT TRANSFER SYSTEM: SKIN FRICTION

The intrinsic nature of the propellant imposes that the internal flow through the hose has to be viscous. The importance of the viscous effects is directly linked to the design parameters of the hose and the characteristics of the internal velocity profile once fixed the propellant type, hence the viscosity.

The presence of the viscosity can be directly translated into its friction effect that acts at the wall of the inner side of the hose. Such effect induces shear at the wall.

The following figure describes the phenomenon.

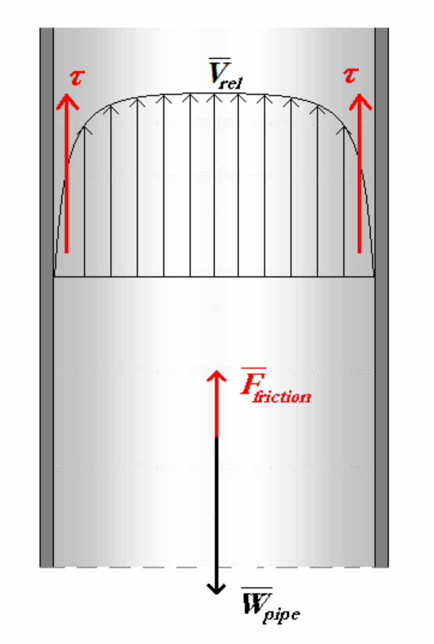

Figure 27 – Skin friction phenomenon

In order to determine the proper order of magnitude, with the scope of foreseeing the possible consequent physical phenomena, one should have a local view of the flow field and a pointwise solution. Such solution would be useful to define with high accuracy the intensity of the shear at the inner wall.

According to the definition, for Newtonian fluids [(19) – *L. De Luca*, 1998], [(20) – *R.A. Granger*, 1985]:

$$\tau_{wall} = \mu \left. \frac{\partial V_{rel}}{\partial R} \right|_{R_{in}(\xi)} \qquad \text{Eq. 35}$$

Where: τ_{wall} is the shear at the wall; μ the dynamic viscosity of the fluid; V_{rel} the component of the relative speed vector of the flow, with respect to the wall, taken along the axial direction of the hose; R the radial variable and R_{in} its value at the wall.

The analytical knowledge of the gradient of the relative velocity might not be simply available, being the problem highly non-linear.

Furthermore, its numerical determination might require a high effort, which is, in this particular case, not required.

According to standard arguments in fluid mechanics and hydraulics one can obtain useful and extensive information using global average values of the flow in a cross section and employing well tested engineering models used to describe a viscous evolved flow in a duct [(7) – *R. V. Giles*, 1962], [(26) – *R. D. Blevins*, 1984], [(25) – *F.M. White*, 1974]:

$$\tau_{wall} = \frac{1}{2}\rho \cdot V_{rel}^2 \frac{f}{4}; \qquad \text{Eq. 36}$$

where ρ is the density of the fluid, in particular the propellant, V_{rel} the mean flow velocity measured by an observer fixed on a hose cross-section and f the friction factor, known as Darcy-Weisbach, or Moody friction factor.

This last term depends on various parameters such as the *Reynolds* number, the hydraulic diameter of the duct, and the roughness of the material at the wall.

It can be seen that the establishment of τ_{wall} is the direct cause for the generation of a sustaining lifting effect of the hose, a pressure loss for viscous phenomena and, ultimately as a consequence, the increase in power to be given to the fluid to supply the pressure pointwise needed in order to let the propellant chase and reach the vehicle's body [(11) – *B. Ancarola*, 2003], [(4) – *AB Technologies*, 2004], [(5) – *B. Ancarola*, *W. Grassi*, *D. Testi*, 2004].

4.9.4 PROPELLANT TRANSFER SYSTEM: SUSTAINING LIFTING EFFECT

The first direct consequence of the establishment of the shear at the wall inner side of the hose is the creation of a sustaining lifting effect. Such effect is indeed the integral consequence of the presence of the shear acting pointwise on a surface that has an extension in space. Moreover, such effect is to be considered as evolving in time as the surface, on which the pointwise phenomenon occurs, evolves during the ascent of the vehicle [(11) – *B. Ancarola*, 2003], [(10) – *B. Ancarola*, *L. Deseri*, 2003], [(5) – *B. Ancarola*, *W. Grassi*, *D. Testi*, 2004].

In order to describe mathematically the phenomenon the rectified co-ordinate taken on the axis of the hose, ξ, has to be considered. This because, in the most generic manner, the length of the hose increases as the vehicle's body ascends.

Such force can be evaluated as surface integral of τ_{wall} as follows [(36) – *B. Ancarola*, *D. Starnone*, *M. Iannuccelli*, *D. Testi*, Dec. 2004], [(59) – *V. Ferone*, 1997]:

$$F_\tau(t) = \int_0^{2\pi} \int_0^{L(t)} \tau_{wall}[\xi(t)] R_{in}[\xi(t)]\, d\vartheta d\xi\,, \qquad \text{Eq. 37}$$

where, the term $L(t)$ is the inner contact length of the inner side of the hose, which is instantaneously wetted by the propellant.

It can be noticed that such force has a positive sign and, with proper dimensioning and design, it can be used in a helpful manner to decrease the effect of the traction force, imposed by the hose, on the motion of the vehicle's body.

Indeed, with proper selection of hose hydraulic diameter and material, the magnitude of the sustaining lifting effect can be of the same order of the one of the traction force.

4.9.5 POINTWISE PUMPING PRESSURE

The task of transferring the propellant from the ground-based reservoir to the lower stage of the vehicle's body remains a duty of the ground based pumping systems. To transfer the propellant the pumping systems must offer to the fluid a force per unit area in the direction of the motion, hence a pressure, able to win the weight of the fluid column evolving in time and its inertia.

The knowledge of the pressure gap versus time law, between the base and the top edges of the hose, is important when the dimensioning of the thickness and the evaluation of the power to be supplied by the pumping systems must be performed. Such pressure gap depends on a potential term and on a viscous term, related to the shear generated at the inner wall of the hose.

The determination of the pressure gap can be obtained by solving the balance of linear momentum. However, an approximate solution may lead to the following [(11) – *B. Ancarola*, 2003], [(36) – *B. Ancarola*, *D. Starnone*, *M. Iannuccelli*, *D. Testi*, Dec. 2004]:

$$\Delta p(t) = \rho_{prop}\left[g + \ddot{z}_{cm}(t)\right]L(t) + \Delta p_{loss}(t), \qquad \text{Eq. 38}$$

where ρ_{prop} is the propellant density and $\ddot{z}_{cm}$ the acceleration of the vehicle's body. The Δp_{loss} term depends on the viscous phenomena occurring in the flow through the hose and its functional dependence can be expressed as follows:

$$\Delta p_{loss}(t) = f\left[\tau[\xi(t)], R_{in}[\xi(t)], t\right]. \qquad \text{Eq. 39}$$

A qualitative plot of the pressure gap is shown in the following figure.

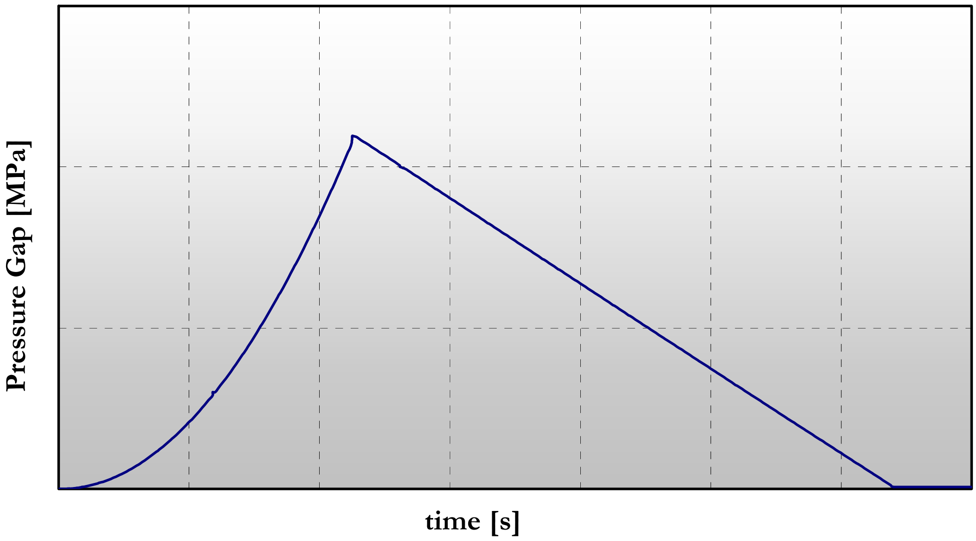

Figure 28 – Qualitative pressure gap versus time law

4.9.6 POINTWISE PUMPING POWER

The estimation of the magnitude of the power that has to be supplied by the pumping systems is another fundamental design point. As it can be expected, such hydraulic power is a varying function of the time.

In particular, considering the physics beneath the problem, it can be expected to be an increasing function of the time, from lift off up to the moment t^*, when the low density fluid is injected through the external feeding line. Afterwards, the time dependence of the power has to be expected decreasing because the liquid column of propellant shortens as the vehicle keeps on gaining height up to the event of the hose release, when the propellant column has vanished. In that moment the hose is fully filled of low-density fluid [(11) – *B. Ancarola*, 2003], [(4) – *AB Technologies*, 2004], [(5) – *B. Ancarola*, *W. Grassi*, *D. Testi*, 2004].

In order to mathematically describe it, the problem can be simplified as the one of a pump that has to move a certain fluid mass from a point located at height zero, (*A*), to one located at a certain height, (*B*), which is instantaneously moving in the vertical direction. Such power can be seen as the integral measure of the hydraulic force necessary to win the weight and the inertia of a fluid column, times the speed of motion of its point of application [(60) – *F. Chorlton*, 1983], [(61) – *F.P. Beer*, 1976].

$$Pow(t) = \int d\underline{F} \cdot \underline{V}\,. \qquad \text{Eq. 40}$$

It must be noticed again that an ideal contribution and a viscous one affect the magnitude of the power. Hence, for this specific hydraulics problem follows [(11) – *B. Ancarola*, 2003], [(4) – *AB Technologies*, 2004], [(36) – *B. Ancarola*, *D. Starnone*, *M. Iannuccelli*, *D. Testi*, Dec. 2004], [(6) – *N.P. Cheremisinoff*, 1990]:

$$Pow(t) = \int_0^{2\pi}\int_0^{R_{in}[\xi(t)]}\int_0^{L_{wetted}(t)} f\left[\rho, z_{cm}(t), \dot{z}_{cm}(t), \ddot{z}_{cm}(t), R[\xi(t)], t\right] d\vartheta dR d\xi +$$

$$+\int_0^{2\pi}\int_0^{L_{wetted}(t)} g\left[\rho, \mathrm{Re}, \varepsilon, \dot{z}_{cm}(t), z_{cm}(t), \ddot{z}_{cm}(t), R[\xi(t)], t\right] d\vartheta d\xi\,, \qquad \text{Eq. 41}$$

where, again *Re* is the Reynolds number and ε the roughness of the material at the inner wall of the hose. The volume integral in the previous equation represents the ideal contribution, while the surface integral represents the viscous contribution. A qualitative plot of the power versus time law is shown in the following figure.

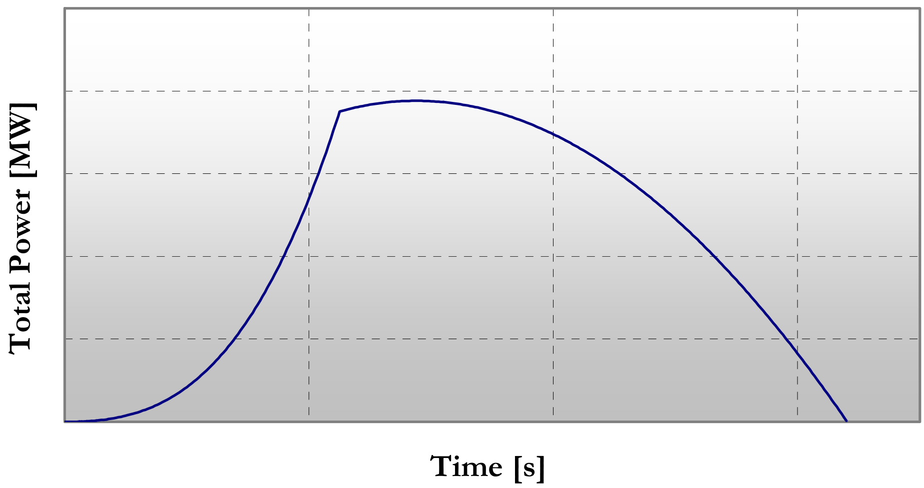

Figure 29 – Qualitative view of the total power versus time law

4.9.7 X-FAST Overall Engineering Equations of Motion till Propellant Transfer System Release

According to the theory and the engineering considerations presented in the previous sections a complete summary of the equations of motion for the vertical ascent of an X-FAST vehicle type can be stated as follows:

$$\frac{d^2 z_{cm}(t)}{dt^2} = \frac{1}{m^{X-FAST}} \Bigg\{ \left[\dot{m}\cdot V_e + (p_e - p_a)A_e\right] - m^{X-FAST} g - \frac{1}{2} C_D(M)\rho_{air}(z_{cm}) z_{cm}^2 A_{front} + \\ + \Bigg[-\rho_{mat}\left[g + \ddot{z}_{cm}\right] \int_0^{2\pi} \int_{R_{in}[\xi(t)]}^{R_{ext}[\xi(t)]} \int_0^{z_{CM}(t)} R\left[\xi(t)\right] d\vartheta dR d\xi + \int_0^{2\pi} \int_0^{L_{wetted}^{prop}(t)} \tau_{wall}^{prop}\left[\xi(t)\right] R_{in}\left[\xi(t)\right] d\vartheta d\xi + \\ + \int_0^{2\pi} \int_0^{L_{wetted}^{gas}(t)} \tau_{wall}^{gas}\left[\zeta(t)\right] R_{in}\left[\zeta(t)\right] d\vartheta d\zeta - \int_0^{2\pi} \int_0^{z_{cm}(t)} \tau_{wall}^{air}\left[\varsigma(t)\right] \mathrm{R}_{ext}\left[\varsigma(t)\right] d\vartheta d\varsigma \Bigg] \Bigg\} \quad \text{.Eq. 42}$$

In particular the last two terms, within their ranges of application, can be neglected since they are of lower orders of magnitude.

4.9.8 Comparative Conventional Launcher Model

When the differences in characteristics of motion and, as a consequence, in performances have to be assessed in order to compare an X-FAST system with respect to a conventional one, a comparative conventional rocket model has to be considered.

The following equations describe the vertical motion of a conventional system:

$$\frac{d^2 z_{cm}(t)}{dt^2} = \frac{1}{m^{conv}(t)} \left\{ \left[\dot{m}\cdot V_e + (p_e - p_a)A_e\right] - m^{conv}(t) g - \frac{1}{2} C_D(M)\rho_{air}(z_{cm}) z_{cm}^2 A_{front} \right\} \quad \text{.Eq. 43}$$

It has to be reminded that the relation linking $m^{X\text{-}FAST}$ and m^{conv} depends on the mission strategy adopted (see paragraph 4.2).

4.10 PERFORMANCE DEFINITION

The assumption is made that, from the separation of the hose, the nature of the motion of the system is identical to a conventional one.

The performance gain definition is delivered in terms of comparisons, with respect to a conventional system, on the vehicle speed and/or other flight parameters up to the moment of pipe's separation.

The performance definition is delivered in terms of comparisons, with respect to a conventional system, on the vehicle speed and/or other flight parameters up to the moment of pipe's separation, and it could be of interest to check and compare the performances by propagating up to the burn out of the first stage.

This is because the X-FAST technology is active only during the functioning of the first stage. The advantages can be extrapolated using consolidated mission analysis methodologies and properties of the final conditions achieved by the vehicle already at the first stage burn out.

It is important to underline that this propagation can be made, without any loss of generality, under the hypothesis of vertical motion. This is to give the conventional and X-FAST device employing vehicles the same possibilities to show their performances, capabilities and potentialities on exactly the same path.

For the reference rocket, fixed the mass of the upper stages and the mission strategy, the reference altitude is defined as follows:

$$h_{ref}\% = \frac{h_{release}}{h_{BO,1^{st}\,stage}} \times 100 \qquad \text{Eq. 44}$$

where: $h_{release}$ is the altitude at which the pipe is released; $h_{BO,1^{st}\,stage}$ is the altitude at which the burn out of the first stage occurs; $h_{ref}\%$ is their percent ratio. The last parameter represents an engineering measure of how tall the pipe is once fully deployed, with respect to how far is the vehicle when the duty of the first stage is over.

As a consequence, the relevant indexes considered for the performance gains evaluation are the following:

maximum altitude gain:

$$\Delta h_{Max}\% = \left| \frac{h_{Max}^{X-FAST}\left(h_{ref}\%\right) - h_{Max}^{conv}}{h_{Max}^{conv}} \right| \times 100 \qquad \text{Eq. 45}$$

velocity gain:

$$\Delta V_{BO,1^{st}\ stage}\% = \left| \frac{V_{BO,1^{st}\ stage}^{X-FAST}\left(h_{ref}\%\right) - V_{BO,1^{st}\ stage}^{conv}}{V_{BO,1^{st}\ stage}^{conv}} \right| \times 100 \qquad \text{Eq. 46}$$

Moreover, the preliminary gains in launch capabilities, which can be achieved through the application of the X-FAST concept, are evaluated on the basis of an optimisation of the ΔV budget, imposing that the potential surplus propellant mass, obtained with the employment of the second strategy, (see chapter 4.2), is numerically appropriately distributed among the upper stages [(25) – *J.F. White*, 1961], [(38) – *H.S. Seifert*, *K. Brown*, 1961].

Again, such observation is visualised in the following figure.

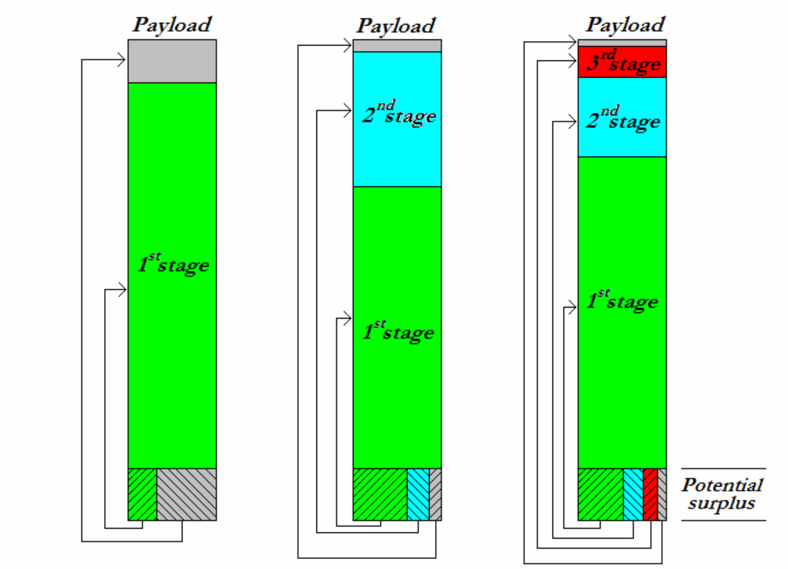

Figure 30 – Potential surplus redistribution scheme for single, double and triple stages rockets, for three different missions/applications types

As a consequence the index describing the gains in launch capabilities is defined as follows:

$$\text{\textit{Gain in Launch Capabilities}}\ [\%] = \frac{B - A}{A} \times 100\,; \qquad \text{Eq. 47}$$

where:

$$A = \frac{m_{payload}^{conv}}{m_{Lift-Off}^{conv}}\,; \qquad \text{Eq. 48}$$

$$B = \frac{m_{payload}^{X-FAST}}{m_{Lift-Off}^{X-FAST}}\,. \qquad \text{Eq. 49}$$

5 PERFORMANCE GAINS ANALYSIS

During the introduction to the X-FAST system the reader was given a preliminary qualitative comprehension of the types of gains to be expected via the application of the proposed technology to a conventional launcher.

Such gains could be intended in different manners depending on the types of mission objectives: higher payload, higher speed at the specific flight phase and condition, lower lift off mass, longer range, higher maximum or apogee altitude, logistics savings, unburdening of the issues related to the generation of power in flight because of the rationalised usage of the ground infrastructure, and other relevant ones [(3) – *B. Ancarola*, *S. Bonifacio*, May 2003].

The current chapter reports the quantitative analysis of the potential types of gains achievable via the application of an X-FAST system to an effectively industrialised conventional rocket, the Ariane 40 launcher.

For such analysis the restrictive hypothesis is made that the ground based pumping systems push the propellant towards the vehicle's body in such manner that the instantaneously incoming mass, which is in liquid phase, numerically equals the mass instantaneously ejected from the nozzle/s of the first stage, in gaseous phase ($\dot{m}_{in} = \dot{m}_{out}$).

The analysis was performed in a parametric manner and the motion of the centre of mass of the vehicle's body was evaluated from lift-off up to hose release, for release altitudes of the X-FAST propellant transfer system ranging from 500 to 5000 [m].

Moreover, the pointwise evaluation of some engineering quantities was performed in order to give the reader an estimate of the orders of magnitudes involved by the application of the X-FAST technology and show that their values are within typical ranges of civil and industrial engineering.

Furthermore the propagation of the motion, under the hypothesis of vertical flight, was performed from hose release up to first stage burn-out and a comparative analysis was made for some flight dynamics quantities achieved at burn-out.

Still an assessment of the preliminary gains in launch capabilities, which can be achieved through the application of the X-FAST concept, was made on the basis of a ΔV budget, imposing that the potential surplus in propellant mass, obtained with the employment of the second strategy (see paragraph 4.2), is appropriately distributed among the upper stages [(44) – *J.F. White*, 1961], [(38) – *H.S. Seifert*, *K. Brown*, 1961].

5.1 MATHEMATICAL MODEL IMPLEMENTATION

The implementation of the mathematical model employed to describe the motion of the centre of mass of the vehicle's body is realised in Matlab environment. It consists in a fully parametric engineering tool which implements the mathematical models previously introduced (see chapter 4) together with others, which are not disclosed.

One of the tasks that the tool performs is the numerical integration of the equations of motion related to the second order Cauchy problem under specified initial conditions on position and velocity [(62) – *L.F. Shampine*, *M.K. Gordon,* 1975]. Such integration can adopt different numerical methods, settable by the designer, such as Runge-Kutta, Adams-Bashforth-Moulton, Rosenbrock formulations [(13) – *R.L. Burden*, *J.D. Faires*, 2001]. The outputs are the evolution in time of the main engineering parameters introduced.

Once configured the design parameters for the selected comparative conventional vehicle, together with the specific parameters defining the X-FAST technology, and fixed the release altitude of the hose, the tool performs a re-dimensioning for the X-FAST employing first stage according to the needs stated in the "Mission Strategies" paragraph 4.2

All the previously presented models are interconnected, one to the other, creating a feed-back system as a fully parametric mathematical model to perform the pointwise evaluation of the flight and engineering parameters versus time. This at the aim of characterising the motion of the centre of mass of the vehicle and the magnitudes of the engineering issues until the X-FAST system is employed.

The following figure shows one of the main block diagrams of the X-FAST engineering tool.

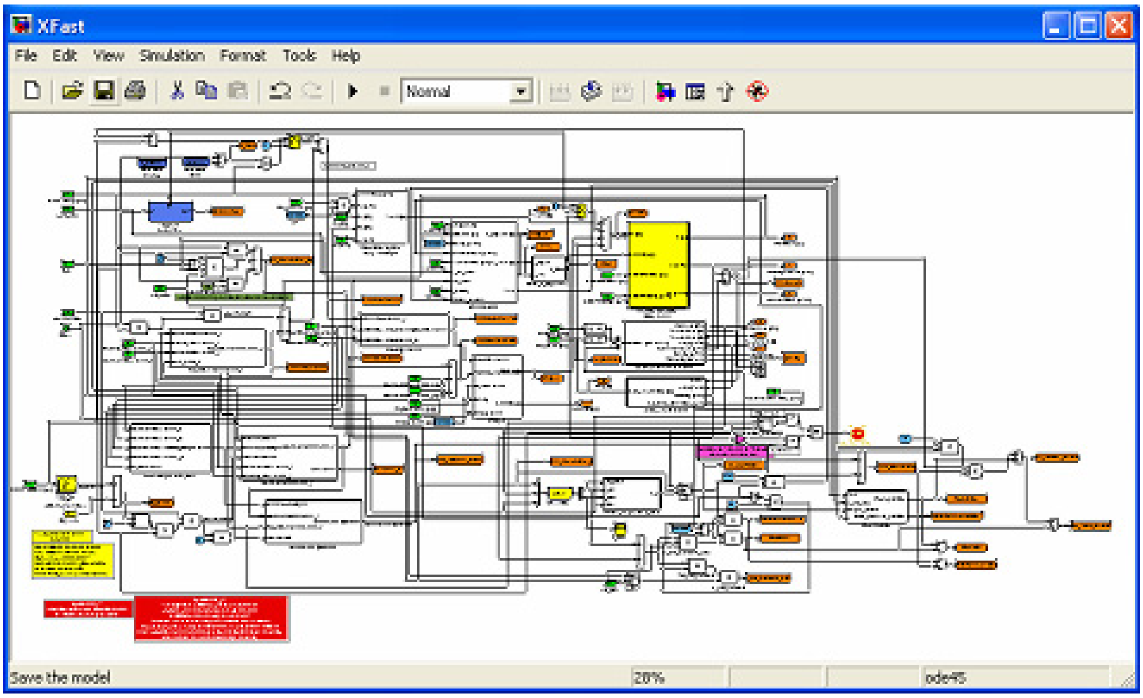

Figure 31 – Overview of the main block diagrams of the feed-back system

From the altitude at which the X-FAST auxiliary device is released, a propagation of the motion of the centre of mass of the vehicle can be performed by means of the tool to evaluate the gains introduced by the X-FAST concept. They can be extrapolated using typical mission analysis methodologies and tools which have been generated.

5.2 MATHEMATICAL MODEL VERIFICATION

The selected launcher for the verification of the models is an Ariane 40 launcher type. In particular an actual flight case [ESA source] has been considered.

For such case the following input parameters have been considered.

- Lift off mass: 267.7 [T];
- Specific impulse in vacuum: 277.68 [s];
- Average mass flow rate: 1104.5 [kg/s];
- Nozzles exit area: 3.24 [m²];
- Frontal surface area: 11.34 [m²].

According to the solution of the equations of motion for the previous input parameters, the following plot shows the matching of the reference solution and the numerical solution obtained by means of the developed mathematical model.

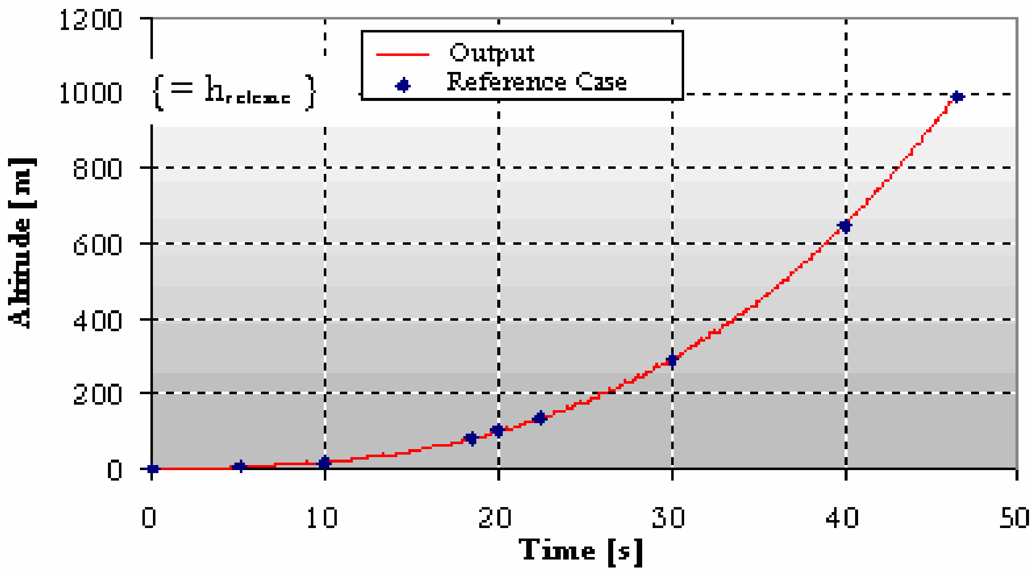

Figure 32 – Verification based on Ariane 40 actual flight case

5.3 X-FAST Application to Ariane 40

In order to verify and apply the mathematical models presented in the previous pages a test case, based on an actual flight case of a conventional rocket, has been selected. A comparison is made between the flight of a vehicle employing an X-FAST system, following mission strategies one and two (as described in paragraph 4.2), with respect to a comparative conventional rocket.

The graphic representation of further engineering parameters as function of time is reported in order to give the reader a pointwise comprehension of their magnitude along the time evolution related to the flight phase during which the X-FAST auxiliary device is employed.

In particular, the reference rocket considered is an Ariane 40 and the evaluation is performed for a conservative case. For such case the X-FAST system release occurs at an altitude of 1 [km]. The following tables and graphs report the main input parameters considered.

Stage	Component	Mass [Kg]
1	Dry Mass	16795
	Propellant (UMDH+N_2O_4)	197346
	Total	**214141**
2	Dry Mass	4471
	Propellant (UMDH+N_2O_4)	34488
	Total	**38959**
3	Dry Mass	1280
	Propellant (LH2+LOX)	10384
	Total	**11664**
Fairing	-	1049
Nominal Payload (GTO)	-	1900
Ariane 40	**-**	**267713**

Table 3 – Ariane 40 – Comparative conventional launcher's mass data [(63) – *ESA*, Oct. 2004]

Stage	Mass Flow Rate [Kg/s]	Nozzle Exit Area [m²]	I_{SP} [s] (Vacuum)
1	1104.50	3.23	277.68
2	272.69	2.24	292.70
3	14.43	1.23	445.80

Table 4 – Ariane 40 – Comparative launcher's propulsion data [(15) – *Arianespace*, 1999]

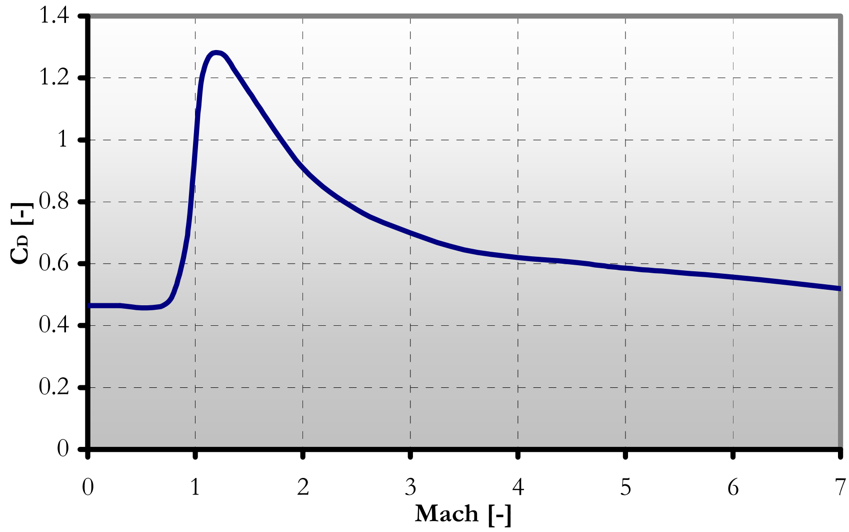

Figure 33 – C_D versus Mach number for zero angle of attack – A_{ref} = 11.34 [m²]

Propellant Transfer System Feature	Value
Cross Section Diameter	0.4 [m]
Wall Thickness	2 [mm]
Hose Material Density	1500 [kg/m³]
Pumped Propellant Density (N_2O_4)	1447 [kg/m³]
Propellant Viscosity (N_2O_4)	$O(10^{-3})$ [kg/(m s)]

Table 5 – Ariane 40 – X-FAST system main input data

The following figures respectively report the altitude, the velocity and the mass versus time for a conventional system and for a modified rocket to which the X-FAST technology is applied.

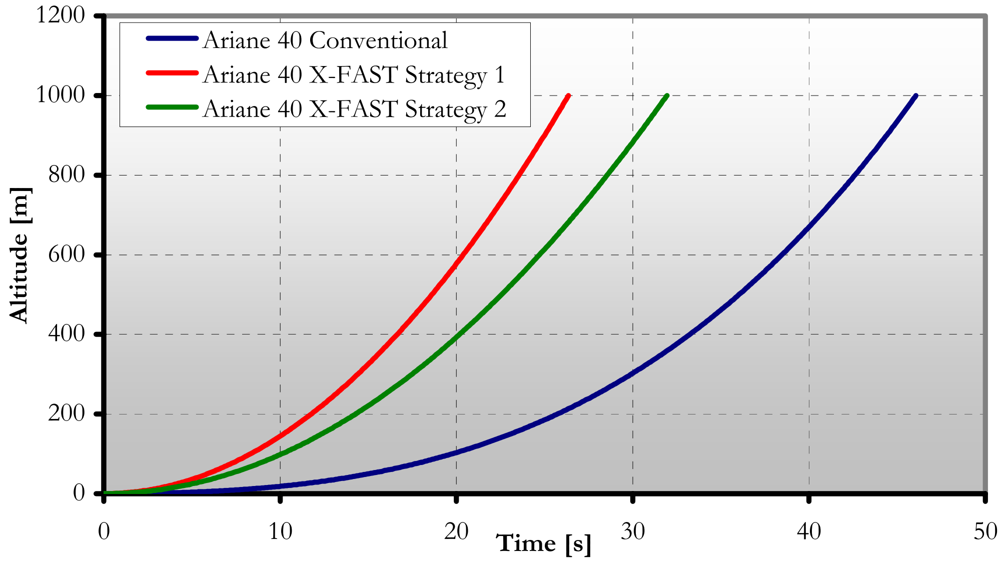

Figure 34 – Altitude versus time for comparative analysis

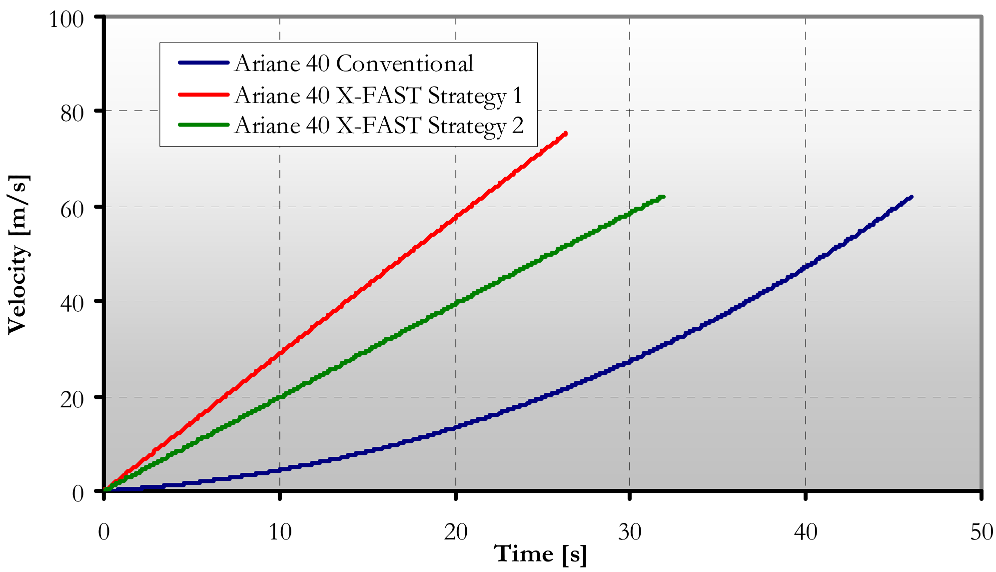

Figure 35 – Velocity versus time for comparative analysis

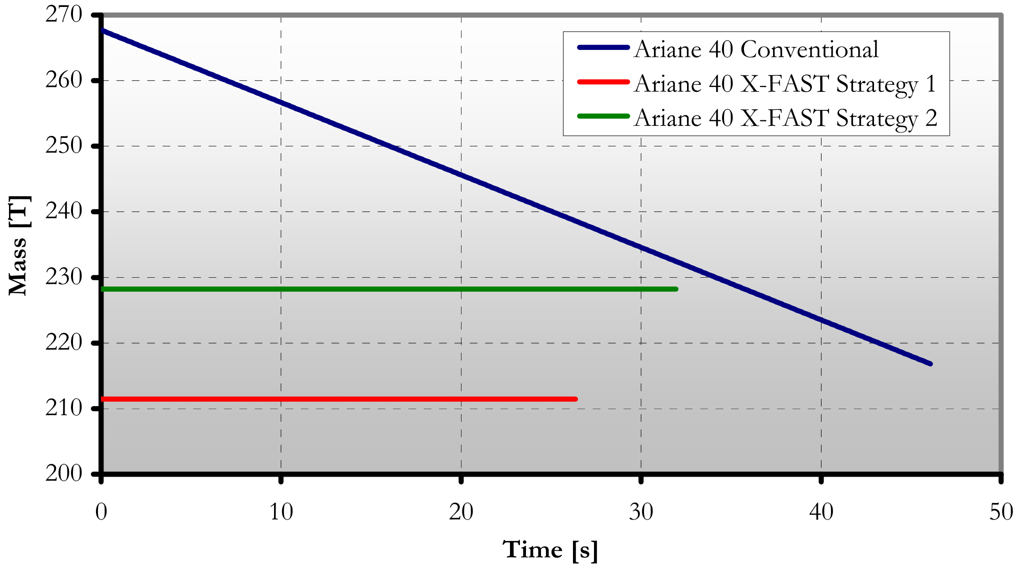

Figure 36 – Mass versus time for comparative analysis

Furthermore, in the following figures the time dependence of the main engineering parameters introduced by the application of the X-FAST technology is reported for the specific first strategy case (see paragraph 4.9).

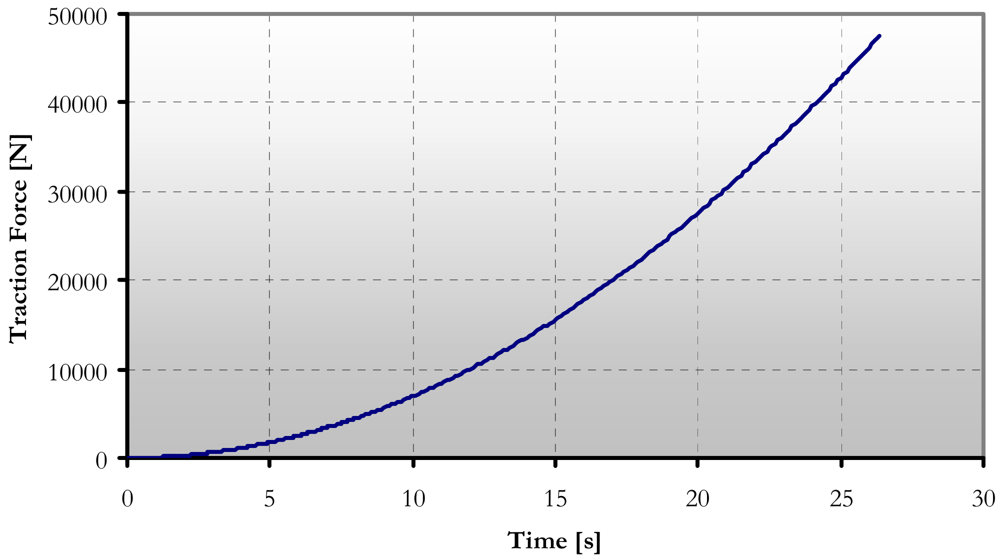

Figure 37 – Traction force versus time

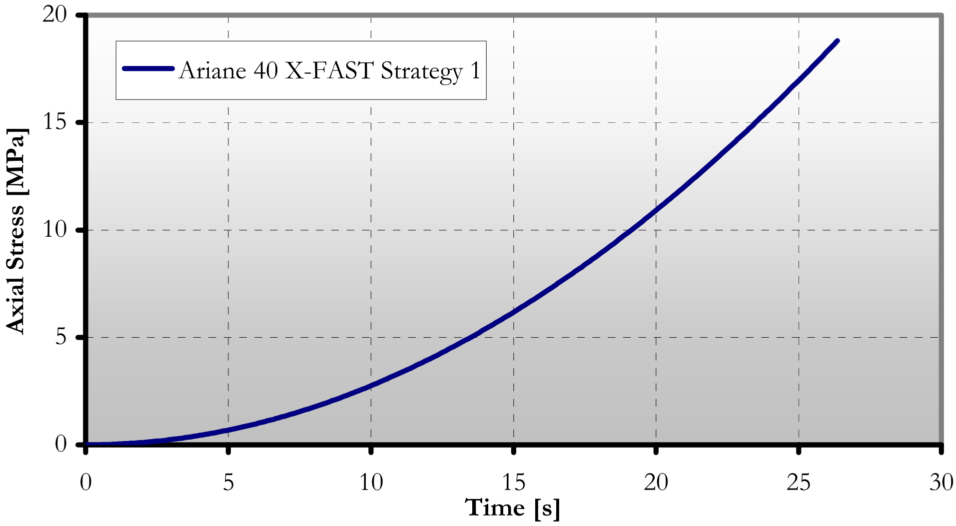

Figure 38 – Axial stress at the connection point versus time

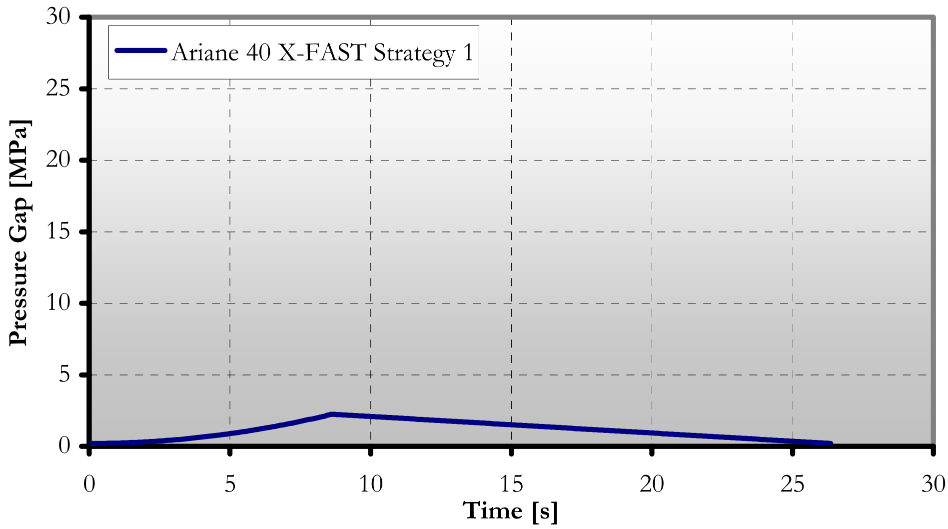

Figure 39 – Pressure gap versus time

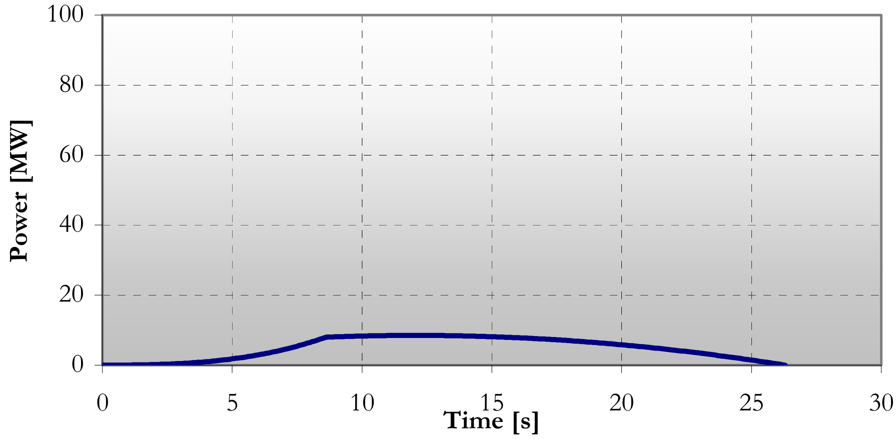

Figure 40 – Power versus time

5.3.1 PARAMETRIC ANALYSIS FROM LIFT-OFF UP TO HOSE RELEASE

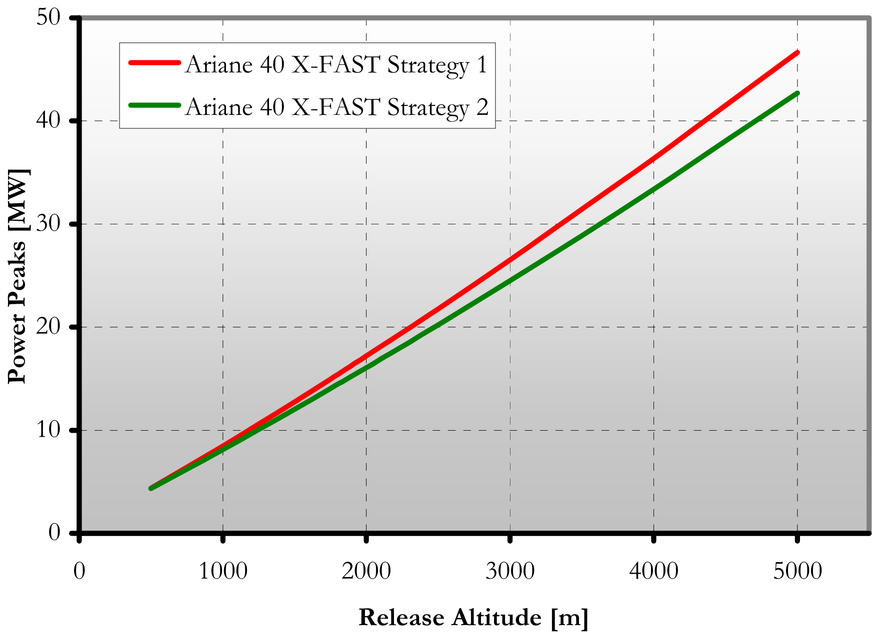

Figure 41 – Ariane 40 – Power peaks versus release altitude

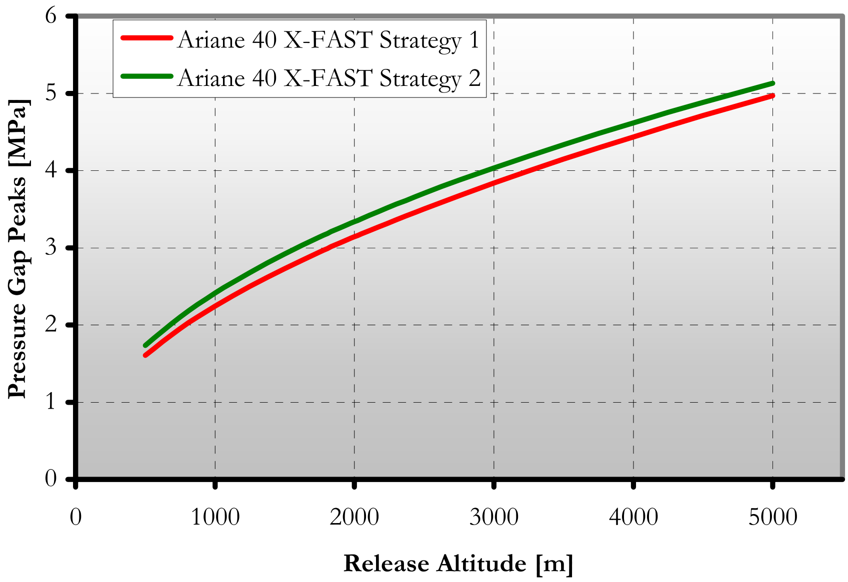

Figure 42 – Ariane 40 – Pressure gap peaks versus release altitude

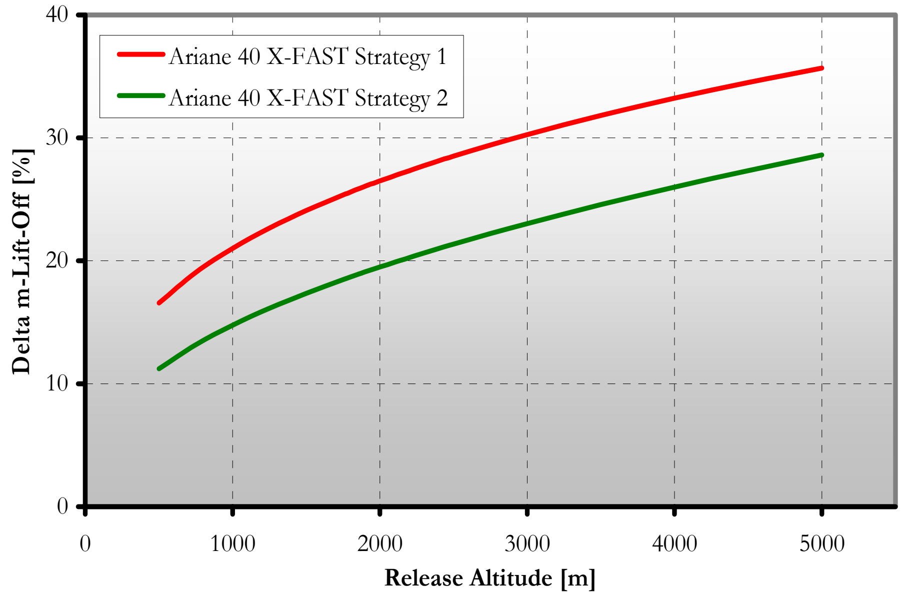

Figure 43 – Ariane 40 – Percentage gain in lift-off mass reduction versus release altitude

5.3.2 Parametric Analysis from Hose Release up to First Stage Burn Out

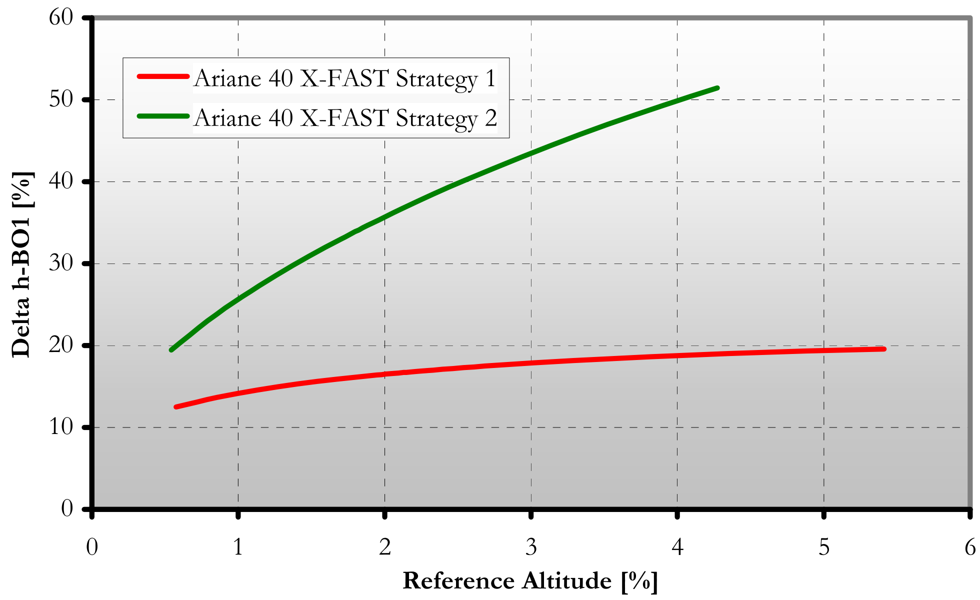

Figure 44 – Ariane 40 – Percentage gain in 1st stage BO altitude versus reference altitude

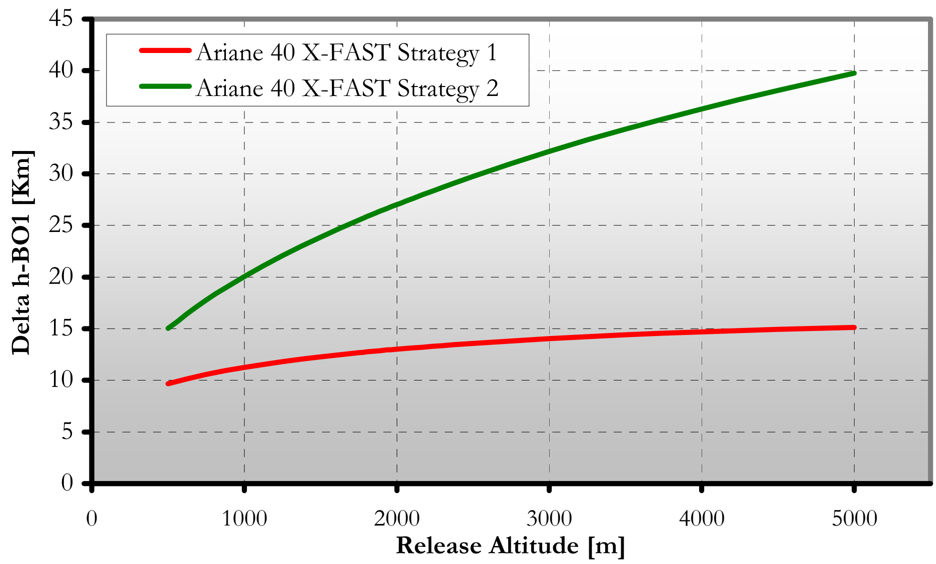

Figure 45 – Ariane 40 – Gain in 1st stage BO altitude versus release altitude

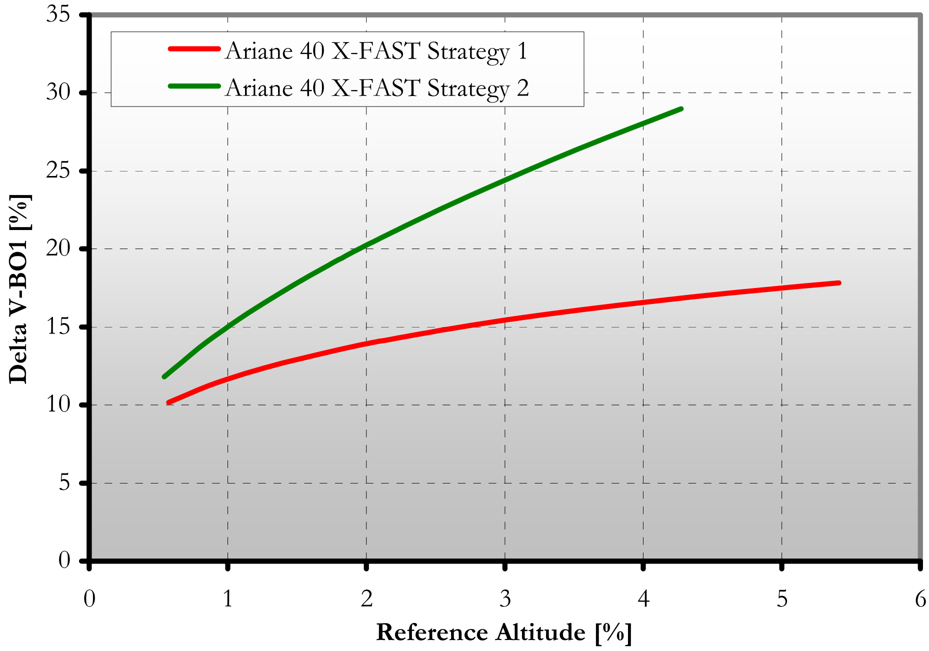

Figure 46 – Ariane 40 – Percentage gain in 1st stage BO speed versus reference altitude

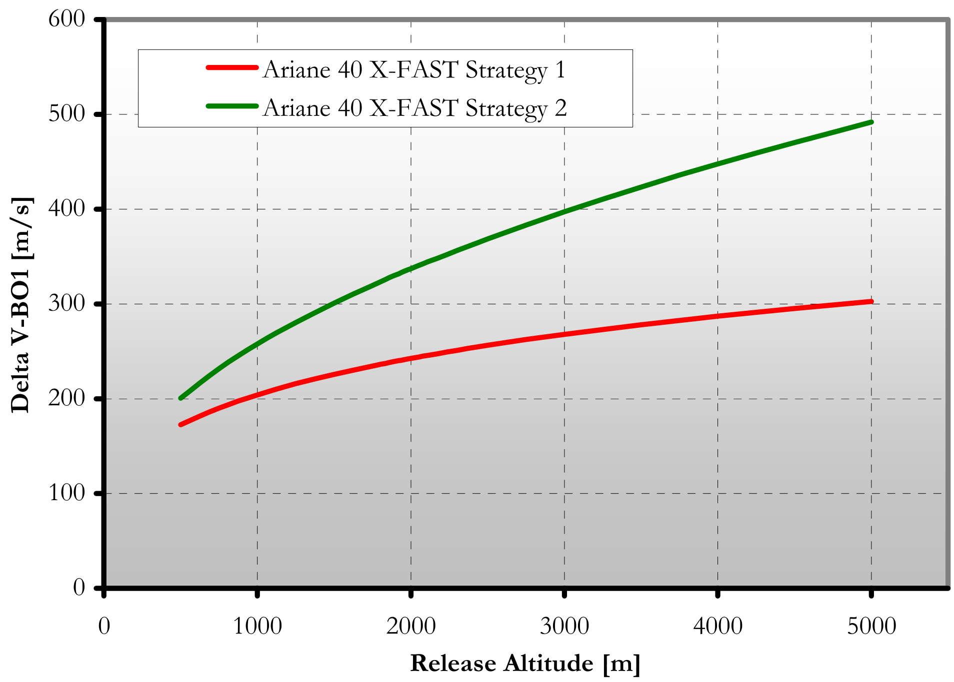

Figure 47 – Ariane 40 – Gain in 1st stage BO speed versus release altitude

5.3.3 Parametric Analysis of the Gains in Launch Capabilities

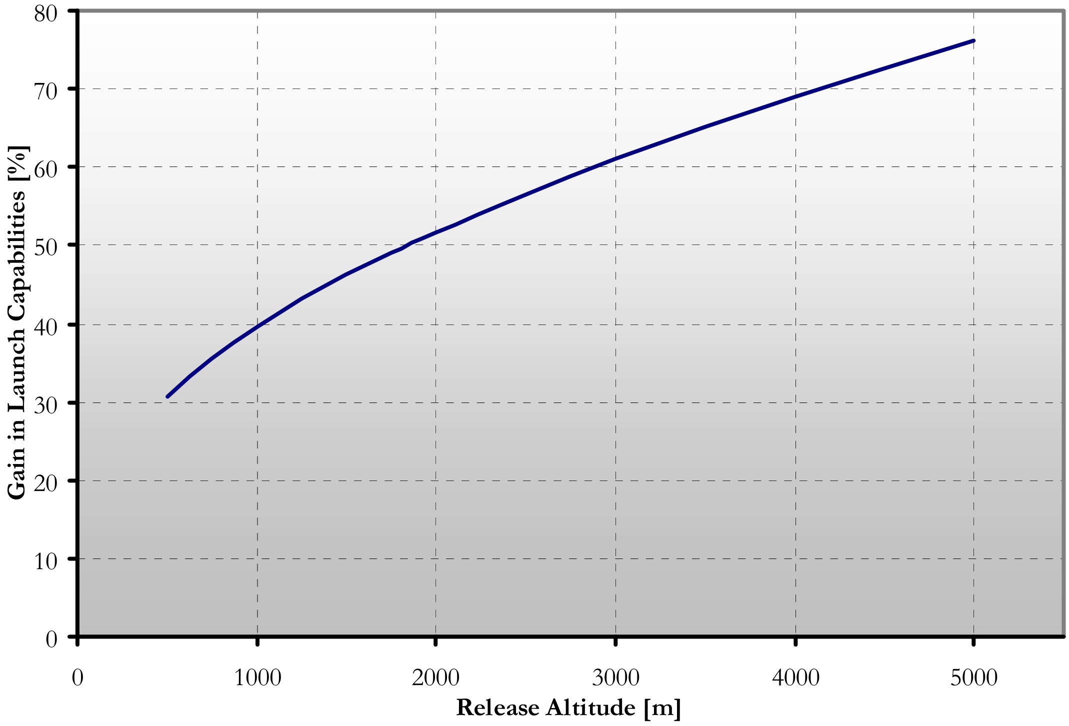

Figure 48 – Ariane 40 – Gain in launch capabilities versus release altitude

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6 CONCLUSIONS

The general view of the X-FAST take-off auxiliary device was given together with the main engineering issues. A mathematical model was described and developed and an analysis of the performance gains, achievable through the application of the X-FAST technology, was performed and the pointwise predicted advantages, foreseen in the previous work, were estimated for an effectively industrialised launch vehicle.

Moreover a parametric analysis of the main engineering quantities involved by the technology was made in order to show their effective orders of magnitude.

As foreseen [(4) – *AB Technologies*, 2004], [(5) – *B. Ancarola*, *W. Grassi*, *D. Testi*, May 2004], and confirmed [(36) – *AB Technologies*, *D. Testi*, Dec. 2004], [(20) – *AB Technologies*, *L. Deseri*, March 2005], such magnitudes remained very limited with respect to the first assessments performed at the earliest stages of the technology research activities, and in typical ranges of industrial applications [(10) – *B. Ancarola*, *L. Deseri*, Aug. 2003], [(11) – *B. Ancarola*, Oct. 2003],

Again, the gains in performances obtained for this study were achieved considering the hypothesis for which the ground based pumping systems push the propellant towards the vehicle's body in such manner that the instantaneously incoming mass, which is in liquid phase, numerically equals the mass instantaneously ejected from the nozzle/s of the first stage, in gaseous phase ($\dot{m}_{in} = \dot{m}_{out}$).

The reader can have a preliminary comprehension of the type of gains achievable via the application of the X-FAST technology to a conventional launcher class by noticing that its employment allows the remarkable reduction in class for size, and the remarkable increase of class for launch capabilities, hence allowing such gains in two directions.

Again, the previous statements can be schematically explained through the following figure representing an in scale modification of an Ariane 40 launcher type to which the X-FAST auxiliary device is applied during the very first part of the flight, in the range of the first 500-1000 meters of the mission.

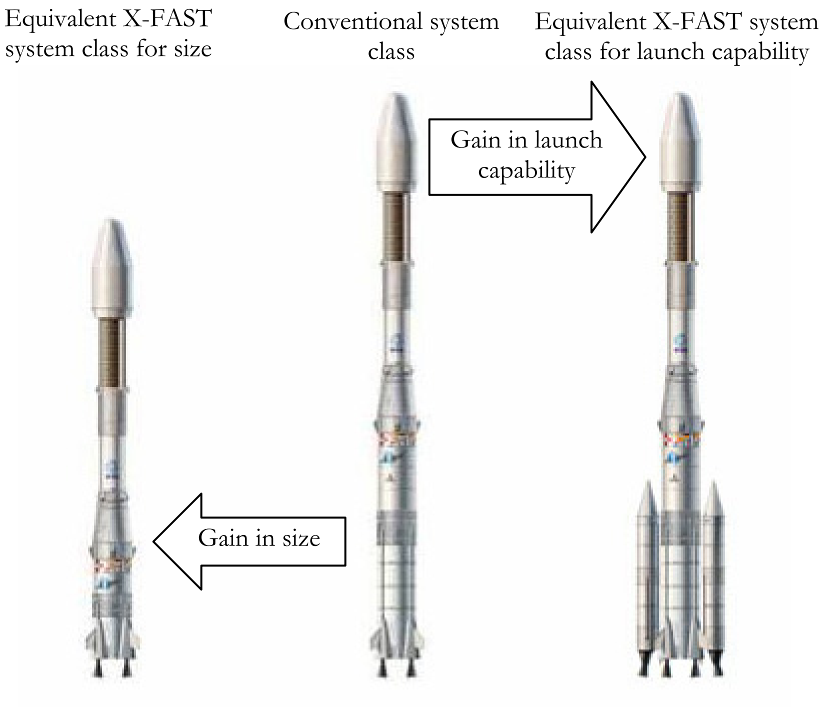

Figure 49 – Explanatory scheme related to the reduction in size and the increase in launch capability

It can be noticed that the previous hypothesis ($\dot{m}_{in} = \dot{m}_{out}$) is a restrictive one; indeed one can think of externally feeding the vehicle's body in such manner that the mass of propellant instantaneously incoming is higher than the one outgoing the nozzle/s of the first stage ($\dot{m}_{in} > \dot{m}_{out}$). Such assumption is equivalent to state that the body of the vehicle is a dynamically increasing mass system. Furthermore, a choice of this type is equivalent to state that, operationally, a fraction of the tanks is kept unloaded at lift-off, while getting filled during the ascent, allowing a further unburdening of the system. Under the last hypothesis further high advantages can be achieved in terms of lightening and re-rationalisation of the X-FAST technology application. However such hypothesis was not considered purpose of this study and further investigations would be of strong interest.

On the other hand, in the frame of the wider X-FAST research project, the conceptual design of a reference case has been performed showing that the main issues related to the feasibility of an X-FAST system can be theoretically proved and that its implementation could occur mainly relying on already existing technologies. In particular the study performed has taken into account as a reference case a small technology demonstrator, which however can be considered an appropriate example for later envisaged typical industrial application.

In the frame of the study the main issues were taken into account and a wide range of engineering disciplines involved by the X-FAST technology were dealt with. In particular several solutions to solve the predicted engineering issues were offered and analyses were performed to define a compatible vehicle's body configuration, propellant transfer system and relative ground based systems.

It was shown that the main engineering issues related to the stability and control, solid mechanics, thermofluid-dynamics and system design were faced and conceptually solved.

Further theoretical and experimental researches are strongly encouraged in order to consolidate the X-FAST pre-stage assisting technology and an appropriate demonstration campaign could definitely create a suitable awareness and consciousness within the scientific and industrial communities.

At this stage the reader can get a feeling about the fact that the X-FAST system shall not be considered as a launcher technology, but as an assisting device, employable in the very first part of the flight, by means of which launchers and general flying vehicles could benefit in performances.

In the history of rocket science, aerospace and aviation in general, for different purposes several types of options for the problem of access to flight have been tested, tried, employed becoming nowadays of common use and essential.

In such frame the X-FAST concept, in the role of strategic and/or alternative asset for the community, has never been considered due to its novelty.

Hence, a full demonstration programme to occur in a short period of time shall be envisaged to start for the benefits of the industrial and scientific communities and for the general public.

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7 REFERENCES

[A] EC-ESA, *White Paper: "Space: a New Frontier for an Expanding Union – An Action Plan for Implementing the European Space Policy"*, Brussels, November 2003.

[B] ESA, "*Dossier 0: Future Prospects, Technology Requirements and Industrial Trends for the European Space Sector"*, ESA IMT-TS, August 1998.

[C] ESA, "*Dossier 0"*, Issue 2, Rev. 2, March 2002.

[D] ESA, "*Resolution on 2010 Perspectives for the European Launcher Sector"*, ESA/C-M/CLXV/Res. 4, adopted in May 2003.

[E] ESA, "*Agenda 2007"*, BR-213, October 2003.

[F] EC, "*Research for a Secure Europe – Report of the Group of Personalities in the Field of Security Research"*, Brussels, 2003.

[G] EC, "*Implementation of the First Action Plan on Innovation in Europe"*, Brussels, 1998.

[1] Wiley J. Larson, James R. Wertz, "*Space Mission Analysis and Design*", Space Technology Library Editions, 2000.

[2] Annamaria Russo Sorge, "*Lezioni di Propulsione Aerospaziale*", Dipartimento di Scienza ed Ingegneria dello Spazio "Luigi G. Napolitano", Università degli Studi di Napoli "Federico II", Napoli, 1984.

[3] Biagio Ancarola, Salvatore Bonifacio, "*Considerations on the Performance Advantages for an X-FAST System*", (Personal discussions), May 2003.

[4] AB Technologies, Internal Documentation, 2004-2005.

[5] Biagio Ancarola, Walter Grassi, Daniele Testi, *"Engineering Observations on the External Feeding Line and Pumping Systems for an X-FAST Concept*", (Private consultancy), Pisa, May 2004.

[6] Nicholas P. Cheremisinoff, "*Practical Fluid Mechanics for Engineers and Scientists*", Techonomic, Lancaster, Pennsylvania, 1990.

[7] Ranald V. Giles, "*Fluid Mechanics and Hydraulics*, 2nd Edition, Mc Graw Hill, 1962.

[8] Von Karman Institute for Fluid Dynamics (V.K.I.), Aeronautics and Aerospace Department, Rhode Saint Genèse, Belgium.

[9] Centro Italiano Ricerche Aerospaziali (C.I.R.A.), Capua, Italy.

[10] Biagio Ancarola, Luca Deseri, "*Engineering Considerations on the Design of the External Feeding System for an X-FAST Concept*", (Private consultancy), August 2003.

[11] Biagio Ancarola, "*Assessment of Some Critical Issues for an Advanced Space Transportation Concept (X-FAST)*", Internal, Issue 1. Rev. 1, 2003.

[12] Vincenzo Ferone, "*Lezioni di Analisi Matematica I*", Dipartimento di matematica ed applicazioni "Renato Caccioppoli", Università degli Studi di Napoli " Federico II", 1996.

[13] Richard L. Burden, J. Douglas Faires, "*Numerical Analysis*", 7th Edition, Brooks/Cole, 2001.

[14] Isakowitz, Steven J, "*International Reference to Space Launch Systems*", 2nd Edition, AIAA, Washington DC, 1991 (succeeded by 2000 edition).

[15] Arianespace, "*Ariane 4 User's Manual*", Issue 2, 1999.

[16] ESTEC-CDF, "*Launcher's Database*".

[17] Biagio Ancarola, "*Ariane 5 Performance Optimisation for Interplanetary Missions*", EWP 2166, ESA/ESTEC, Noordwijk, The Netherlands, March 2002.

[18] L.D. Landau, E.M. Lifshitz, "*Theory of Elasticity*", 2nd Edition, Institute of Physical Problems, USSR Academy of Sciences, Pergamon Press, 1970.

[19] Luigi De Luca, "*Lezioni di Termofluidodinamica*", Dipartimento di Energetica, Termofluidodinamica Applicata e Condizionamento Ambientale, Università degli Studi di Napoli "Federico II", 1998.

[20] Robert A. Granger, "*Fluid Mechanics*", CBS College Publishing, New York, 1985.

[21] Technical University of Delft, "*IdeMat*", 2002.

[22] ESA, "*Structural Materials Handbook*", Structures and Mechanisms Division, European Space Research and Technology Centre (Document: ESA PSS-03-203), Noordwijk, The Netherlands, February 1994.

[23] John F. Harvey, "*Theory and Design of Pressure Vessels*", Van Nostrand Reinhold Company, New York, 1985.

[24] S.P. Timoshenko, J.N. Goodier, "*Theory of Elasticity*", 3rd Edition, Mc Graw Hill Editions, 1970.

[25] F.M. White, "*Viscous Fluid Flow*", Mc Graw Hill, New York, 1974.

[26] Robert D. Blevins, Ph.D., "*Applied Fluid Dynamics Handbook*", Van Nostrand Reinhold Inc., 1984.

[27] Luigi G. Napolitano, "*Appunti di Gasdinamica*", Napoli, 1969.

[28] Ferri, "*Elements of Aerodynamics of Supersonic Flow*", MacMillan, New York, 1949.

[29] F. Sabetta, "*Gasdinamica*", Edizioni Ingegneria 2000, Roma, 1999.

[30] G.P. Sutton, "*Rocket Propulsion Elements*", 6th edition, John Wiley & Sons, 1992.

[31] A.C. Wright, "*USAF Propellant Handbook: Nitric Acid/Nitrogen - Tetroxide Oxidizers – Vol II*" Contract F04611-76-C-0026, Martin Marietta Corporation, Denver – Colorado. February 1977.

[32] Francis A. Warren, "*Rocket Propellants*", Reinhold Publishing Corporation, 1958.

[33] ESA, "*Data for Selection of Space Materials*", Product Assurance & Safety Department, European Space Research and Technology Centre – ESA PSS-01-701, Issue 1 Rev.3, January 1994.

[34] NASA, "*TPSX Material Properties Database*", Version 4, 2003.

[35] S. Fouche, *"Motors for Aggressive Fluids – Final Review – Materials/Fluids Compatibility Study (Bibliographic and Experimental"*), Chemistry Laboratory, ESA/ESTEC, Noordwijk, The Netherlands, June 10th 1992.

[36] Biagio Ancarola, Davide Starnone, Marco Iannuccelli, Daniele Testi, "*Engineering Observations on the External Feeding Line and Pumping Systems for an X-FAST Concept*", (Private consultancy), Noordwijk, The Netherlands, December 2004.

[37] O.H. Lange, R.J. Stein, "*Space Carrier Vehicles*", Advances in Space Science and Technology, Supplement 1, Academic Press Inc., 1963

[38] Howard S. Seifert, Kenneth Brown, "*Ballistic Missile and Space Vehicle Systems*", University of California, John Wiley & Sons Inc., 1961.

[39] Robin G.J. Biesbroek, Biagio P. Ancarola, *"Optimisation of Launcher Performance and Interplanetary Trajectories for Pre-Assessment Studies*", ESTEC-CDF, Università degli Studi di Napoli "Federico II", A-6-07-IAF, Houston TX, USA, October 2002.

[40] E.F. Bruhn, J.I. Orlando, J.F. Meyers, "*Missile Structures – Analysis and Design*", Tri-State offset Company, USA, 1967.

[41] A. D'Anna, P. Renno, "*Elementi di Meccanica Razionale*", Cuen, 1991

[42] A. Maio, "*Lezioni di Meccanica Razionale*", Dipartimento di Matematica ed Applicazioni "Renato Caccioppoli", Università degli Studi di Napoli "Federico II", 1997.

[43] American National Standards Institute, "*Recommended Practice for Atmospheric and Space Flight Vehicle Coordinate Systems*", American National Standard ANSI/AIAA R-004-1992, February 1992.

[44] J.F. White, "*Flight Performance Handbook for Powered Flight Operations*", Space Technology Laboratories Inc., John Wiley & Sons Inc., 1961.

[45] David A. Vallado, "*Fundamentals of Astrodynamics and Applications*", McGraw-Hill 1997.

[46] J.R. Vetter, S.R. Nerem, P.J. Cefola, H. Hagar, "*A Historical Survey of Earth Gravitational Models Used in Astrodynamics from Sputnik and Transit to GPS and TOPEX*", Proceedings of the AAS/AIAA Astrodynamics Conference, Aug 16-19, 1993, Victoria, B.C., V.85, Part II, p. 1233.

[47] Daniel J. Fonte Jr., Ronald J. Proulx, Paul J. Cefola, "*Implementing a 50x50 Gravity Field Model in an Orbit Determination System*", Proceedings of the AAS/AIAA Astrodynamics Conference, Aug. 16-19, 1993, Victoria, B.C., V.85, Part III, p. 2369.

[48] Jess Andrew Marshall, "*Effect of Gravity Model Error on Determining Sea Surface Variability Using Satellite Altimetry*", Masters Thesis, University of Colorado, 1988.

[49] US-D.o.D., "*Department of Defense World Geodetic System 1984, Its Definition and Relationship with Local Geodetic Systems*", NIMA TR8350.2, USA, 1984.

[50] R.A. Minzner, K.S.W. Champion, H.L. Pond, "*The ARDC Model Atmosphere, 1959*", Air Force Surveys in Geophysics No. 115 (AFCRC-TR-59-267), Air Force Cambridge Research Centre, 1959.

[51] SAE Aerospace, "*Applied Thermodynamics Manual*", 3rd Edition, Society of Automotive Engineers, 1969.

[52] R.E. Smith, G.S. West, "*Space and Planetary Environment Criteria for Use in Space Vehicle Development*", 1982 Revision (Volume 1), NASA TM 82478, 1983.

[53] A.S. Jursa, "*Handbook of Geophysics and the Space Environment*", Air Force Geophysics Laboratory, 1985.

[54] COESA, "*U.S. Standard Atmosphere*", U.S. Government Printing Office, Washington DC, 1976.

[55] Rodolfo Monti, Raffaele Savino, "*Aerodinamica*", Napoli, 1998.

[56] J.N. Nielsen, "*Missile Aerodynamics*", formerly NACA, McGraw-Hill, USA, 1960.

[57] John D. Anderson, "*Fundamentals of Aerodynamics*", 2nd Edition, McGraw-Hill, 2001.

[58] S.S. Chin, "*Missile Configuration Design*", The Martin Company, Orlando, Florida, USA, McGraw-Hill, 1961.

[59] Vincenzo Ferone, "*Lezioni di Analisi Matematica II*", Dipartimento di Matematica ed Applicazioni "Renato Caccioppoli", Università degli Studi di Napoli " Federico II", 1997.

[60] F. Chorlton, "*Textbook of Dynamics*", 2nd Edition, John Wiley & Sons, 1983.

[61] Ferdinand P. Beer, E. Russel Johnson, Jr., "*Mechanics for Engineers – Dynamics*", 3rd Edition, Mc Graw Hill, 1976.

[62] L.F. Shampine, M.K. Gordon, "*Computer Solution of Ordinary Differential Equations: the Initial Value Problem*", W. H. Freeman, San Francisco, 1975.

[63] ESA Source, October 2004.

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